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Electrical REVIEW

WIND TUNNELS FOR HIGHEST AIR SPEEDS EVER DEVELOPED...PAGES 8-24

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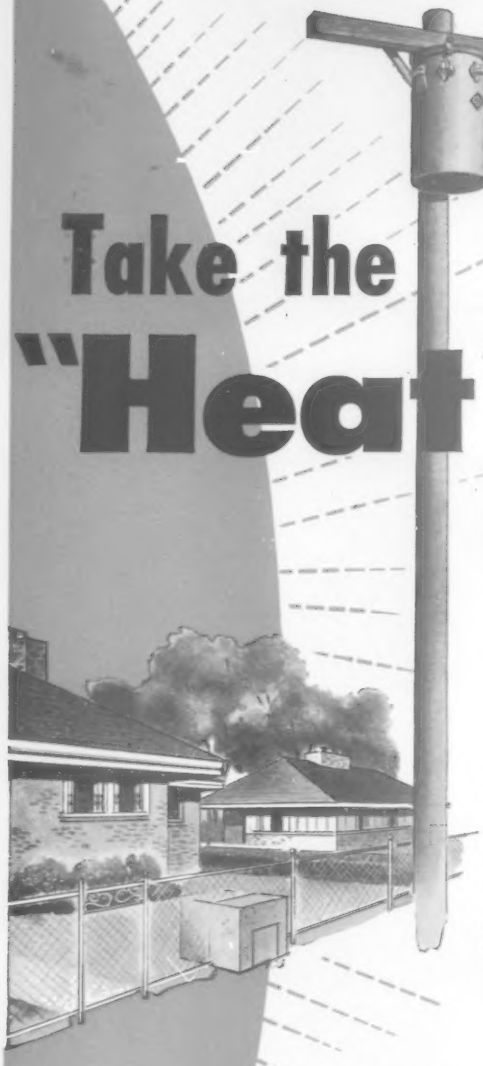
TRANSFORMERS

Take the "Heat Off"

hot weather overloads

— with Low-Cost *Thermalite* Indicators



The heat's on the distribution engineer when air conditioning loads go up. Here's how you can cool off the problem. Use *Thermalite* indicators to get advance warning that overloads are nearing the limits of transformer capability. You don't need time-consuming load surveys because a *Thermalite* indicator's clear signal light can be seen from a service truck. You get continuous, automatic indication of which units need attention. And you get it in time to make changes without disturbing service continuity.

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A-4639

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ALLIS-CHALMERS Electrical REVIEW

THE COVER

UNDERWATER high potential testing dramatizes the outstanding moisture resistance and high dielectric strength of a new, all-silicone-rubber insulating system recently developed for form-wound motor and generator stator coils. Far more significant than the fish bowl demonstration is a laboratory test now being conducted in which 8400 volts — 50 percent more voltage than the standard one-minute high potential test for the 2300-volt coils — has already been applied continuously for more than six weeks!

A-C Staff Photo by Clarence Hansen

Allis-Chalmers

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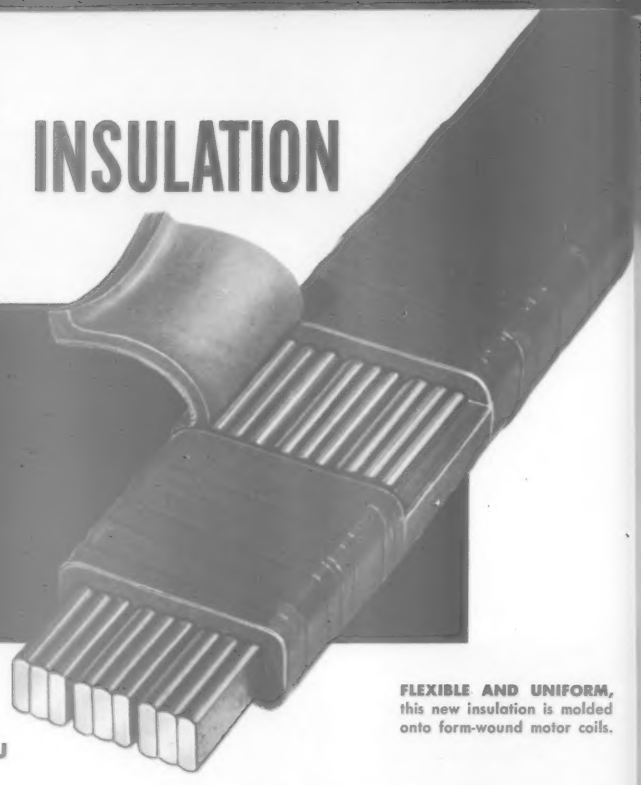
SILCO-FLEX INSULATION

OPENING the way to longer motor life



FLEXIBLE AND UNIFORM, this new insulation is molded onto form-wound motor coils.

by **J. L. KUEHLTHAU**
Engineer-in-Charge
Motor and Generator
Insulation Design
and
P. A. KRYDER
Motor and Generator Department
Allis-Chalmers Mfg. Co.

Now, the long held promise of an all-silicone-rubber insulation system has become reality on electrical rotating machinery.

A NEW INSULATION SYSTEM for motor and generator stator windings — one that may well precipitate a complete re-evaluation of present-day motor enclosure application practices — has recently been developed. Designated the *Silco-Flex* insulating system, this new approach to coil insulation will assure extended life and more dependable operation of motors and generators even under adverse service conditions.

The basic material in this system is a silicone elastomer, one of many new and unique synthetic insulating materials introduced during the past decade.

The silicones have always displayed outstanding characteristics as insulating materials. Silicone resins have already proven valuable for coating fabrics and for bonding mica in conventional insulating systems. Silicone elastomers, frequently referred to as silicone rubbers, are highly stable, resilient materials which have held even greater promise for the insulation of rotating electrical equipment. Until now, however, silicone rubber has been only a promising material because of application difficulties.

Early silicone rubbers required fabric supporting mediums to give them needed mechanical strength. Like conventional coated fabric systems, these insulations lacked conformability and presented fabricating problems.

Recently, the development of unsupported silicone-rubber film materials has been rapid. In addition, new production and application methods for molding this improved material on stator coils, see Figure 1, have been developed. For the first time, the outstanding physical and electrical properties of this material are being used to full advantage in the *Silco-Flex* insulation system.

Improved insulating systems needed

While conventional insulating systems have been reasonably satisfactory over the years, limitations have always been apparent. In the past, coil insulations have been built up from layers of tape or sheet material, as shown in Figure 2. Usually a binder has been used as a filling and sealing material between layers, and multiple coats of varnish have been applied for finishing. To obtain a void-free insulating wall, processing has been complicated and somewhat uncertain.

TABLE I

ELECTRICAL PROPERTIES	THERMAL AND MECHANICAL PROPERTIES	CHEMICAL PROPERTIES
Dielectric Strength	Form Stability	Thermal Stability
Voltage Endurance	Flexibility and Resiliency	Flammability
Dielectric Loss	Resistance to Repeated Physical Stress	Arc Resistance
Dielectric Constant	Abrasion Resistance	Corona Resistance
Volume and Surface Resistivity	Thermal Conductivity	Fungus Resistance
		Non-Corrosive
		Resistance to Contaminants
		a. Moisture
		b. Oil
		c. Solvents
		d. Chemical or Corrosive Atmospheres

In addition, conventional insulating materials have had limited flexibility, particularly after aging. Moisture resistance has been only fair, and thermal stability has been limited by the organic binders used. The use of recently developed silicone resins as binders overcame the limitations of poor thermal stability, but other weaknesses remained.

In contrast, stator coils insulated with *Silco-Flex* silicone-rubber insulation have the conductor and coil insulation vulcanized into a void-free homogeneous insulating wall which is completely sealed even at the leads. This coil insulation more closely fulfills the requirements of an ideal stator coil insulation than any system yet developed.

Obviously, the main job of an insulation is to isolate current-carrying conductors from each other and from adjacent metal parts. Dielectric strength, or the ability to withstand voltage stresses without rupturing, is its basic requirement. Also, an insulating material must initially lend itself to economical application.

Literally hundreds of materials and combinations of materials now available will, to a reasonable degree, fulfill these requirements. However, once a machine begins running, many additional factors, including heat, voltage stress, moisture and vibration, bring their influence to bear on the insulation, and tend to destroy its original qualities. Consequently, in addition to meeting initial requirements, an insulation should remain relatively unchanged by all the attacking elements associated with machine use.

The properties required of an insulation system to meet initial and operating conditions at power frequencies can be grouped into three classifications: electrical, mechanical, and chemical. Individual properties in each classification have been arbitrarily grouped in Table I. When measured against these criteria, the *Silco-Flex* insulating system scores remarkably well.

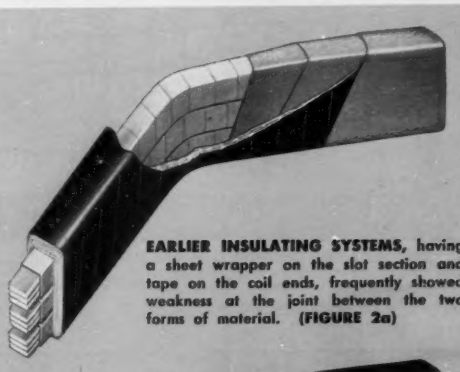
Electrical properties superior to other materials

While most common insulating materials have adequate initial dielectric strength, few retain this characteristic at extreme temperatures or after long aging. Figures 3 and 4 indicate how the dielectric strength of *Silco-Flex* insulation is virtually unaffected by temperatures of 180 C or more.

All insulating materials exhibit dielectric fatigue, or a lowering of dielectric strength, after voltage has been applied for a period of time. Again, most insulating materials have a satisfactory voltage endurance level, but silicone rubber has a remarkably flat time-voltage curve, compared to conventional resin-bonded mica combinations. This represents an extra margin for silicone rubber.

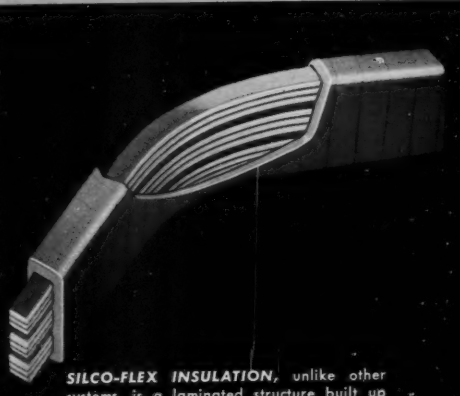
A good indicator of insulation quality is its dielectric loss, as indicated by its power factor. For instance, a rise in power factor with increased temperature, or after aging, can indicate possible instability or poor aging characteristics. Perhaps more important, a change in power factor with voltage change is an indication of voids in the insulating material. Where gas voids are present, any increase in voltage causes the gas to ionize and increases the power factor. The void-free nature of *Silco-Flex* insulation, compared to a conventional insulation, is indicated by the power factor vs. voltage curves in Figure 5.

THESE *SILCO-FLEX* insulated form-wound stator coils are for machines ranging in voltage from 2300 to 13,800. **(FIG. 1)**

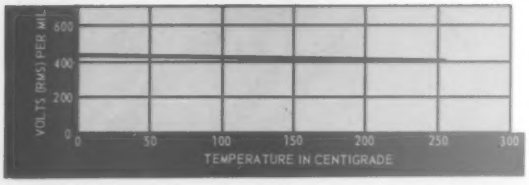


EARLIER INSULATING SYSTEMS, having a sheet wrapper on the slot section and tape on the coil ends, frequently showed weakness at the joint between the two forms of material. **(FIGURE 2a)**

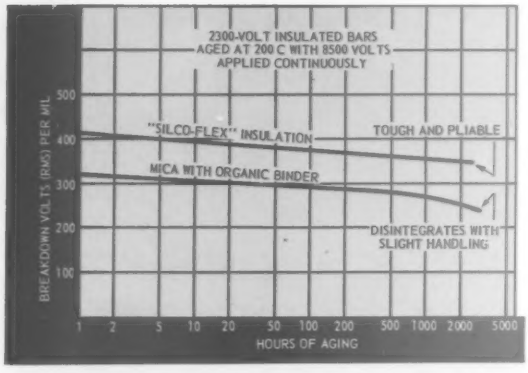
CONTINUOUS TAPING over slot section and coil ends typifies conventional all-tape insulation systems which are built up from dissimilar materials. **(FIGURE 2b)**



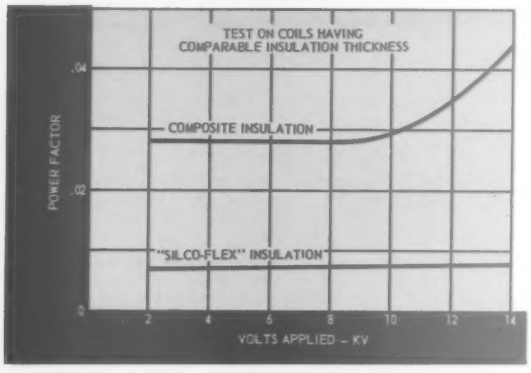
SILCO-FLEX INSULATION, unlike other systems, is a laminated structure built up of only one material, silicone rubber, vulcanized into a homogeneous, void-free dielectric barrier. **(FIGURE 2c)**



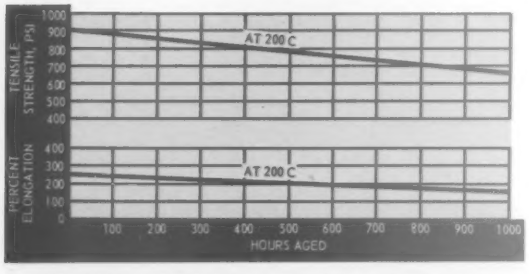
DIELECTRIC STRENGTH of *Silco-Flex* insulation remains high with little change over a wide temperature range. **(FIGURE 3)**



ACCELERATED AGING tests indicate this new insulation retains its higher dielectric strength and superior mechanical properties longer than conventional insulations. **(FIGURE 4)**



VOID-FREE NATURE of *Silco-Flex* insulation is indicated by the flatness of its power factor curve. **(FIGURE 5)**



MECHANICAL PROPERTIES of the silicone rubber used in this new insulating system remain relatively unchanged during oven aging. **(FIGURE 6)** *Courtesy Dow Corning Corp.*

Most dielectrics have adequate initial volume and surface resistivity. *Silco-Flex* insulation, because of its unusual thermal stability and moisture resistant characteristics, maintains high insulation resistance. In contrast, conventional organic materials eventually undergo thermal breakdown, crack, and become partial conductors.

Thermal and mechanical properties also superior

In addition to adequate electrical properties, an insulating material should have good thermal conductivity. All the heat generated in the copper conductors of a winding must be dissipated through the insulating walls surrounding the coils. The higher the thermal conductivity of the insulation, the better the flow of heat away from the copper conductors and, other factors being equal, the cooler the windings will be. *Silco-Flex* insulation has significantly higher thermal conductivity than conventional insulations.

Silicone rubber also displays good form stability. Unlike thermoplastic materials, which tend to flow — with consequent loosening of slot sticks, cording, and blocking — silicone rubber will not flow. It does exhibit, in common with organic rubbers, the property of compression set. However, in machine windings, this represents only a partial relaxation at pressure points rather than a flowing away of material. This is true even at temperatures of 180 C and higher.

While exhibiting the general appearance and elasticity identified with ordinary natural and synthetic rubbers at room temperature, silicone rubber alone retains its flexibility and resiliency relatively unchanged over the extremely wide temperature range of — 60 to 250 C. These characteristics are also retained after thermal aging, as indicated by Figure 6.

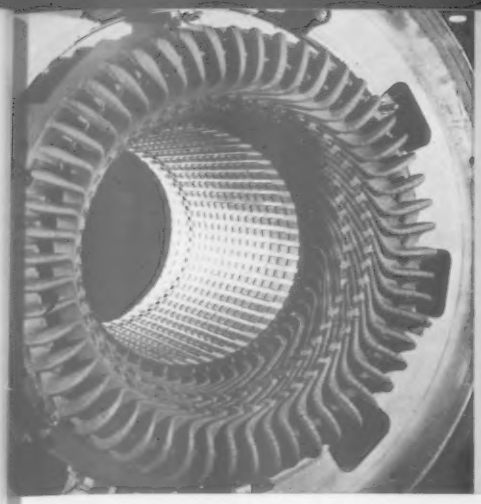
The fatigue life of silicone rubber is high, even when subjected to repeated stresses. This property is retained at elevated temperatures. In a winding, this characteristic, coupled with flexibility, resiliency, and shock resistance, enables *Silco-Flex* to withstand vibration and the constant expansion and contraction of adjoining metal parts.

Abrasives are sometimes responsible for insulation damage, especially in areas of heavy atmospheric contamination. Test bars subjected to sand blasting show only surface erosion of *Silco-Flex*, while the best mica-resin insulated bars, subjected to the same test, were eroded to bare copper, as shown in Figure 8.

Desirable chemical properties are displayed

Chemically, there is no unsaturation in the base polymer of silicone rubber. Neutral in reaction, it refuses to react with most common materials. Thus it is relatively inert to attack by reactive agents. In general, it is resistant to most weak acids and alkalis, salt solutions and oils, and is suitable for use in many chemical or corrosive atmospheres.

Another quality of the *Silco-Flex* insulating system is high corona resistance. Corona can occur in a winding wherever air is in series with solid insulation, and a voltage stress high enough to ionize the air exists. This can normally occur at several locations, including voids in the insulating wall, points of high electrical stress at the end of the core, and between coil ends of opposite phases.



SILCO-FLEX **insulated stator for a 2500-hp, 2300-volt, 2-pole induction motor. (FIG. 7)**

COMPARATIVE ABRASION RESISTANCE of this new insulation was demonstrated by a one-minute sandblast test. (FIGURE 8)

Corona can deteriorate insulation in two ways: by chemical deterioration and by ionic bombardment. The ozone formed by an electrical discharge is a strong oxidizing or bleaching agent, and accounts for the whiteness of "corona spots" on high voltage windings. Also, in the presence of moisture this ozone reacts chemically with nitrogen in air to produce nitrous acid, which attacks organic materials.

Ionic bombardment is, as the name implies, a physical impingement of charged ions against the insulation. Where the voltage stress is high enough, this bombardment can, in time, drill pinholes even through mica. Resistance of silicone rubber to both chemical and ionic deterioration is outstanding and approaches that of mica. Tests indicate that *Silco-Flex* insulation will be suitable for the windings of even the highest voltage motors and generators now in commercial use.

Arc resistance of *Silco-Flex* insulation is very high, in the order of 200-250 seconds, because silicone rubber, unlike the organics, does not readily form an electrically conducting track under an arc.

Silicone rubber has extreme thermal stability. All of its initial characteristics are retained after long exposure to high temperatures. It can withstand temperatures in the range of 180 C continuously and temperatures up to 250 C for a short time without decreasing life or reliability.

If ignited, thin strips of the silicone rubber used in *Silco-Flex* insulation will burn, leaving an ash composed mainly of silica and inert fillers. In heavier sections, such as in coils, *Silco-Flex* insulation is considered to be self-extinguishing when the external flame is removed.

Silco-Flex insulation resists contaminants

For certain specific applications, it is essential that an insulating material have high resistance to contaminants.

In common with all silicones, *Silco-Flex* insulation displays extreme resistance to moisture. In addition, it has a highly water repellent surface which prevents moisture from condensing in a continuous film. Under moisture condensing conditions which would cause flashover or failure of conventional insulations, *Silco-Flex* maintains its high dielectric properties.

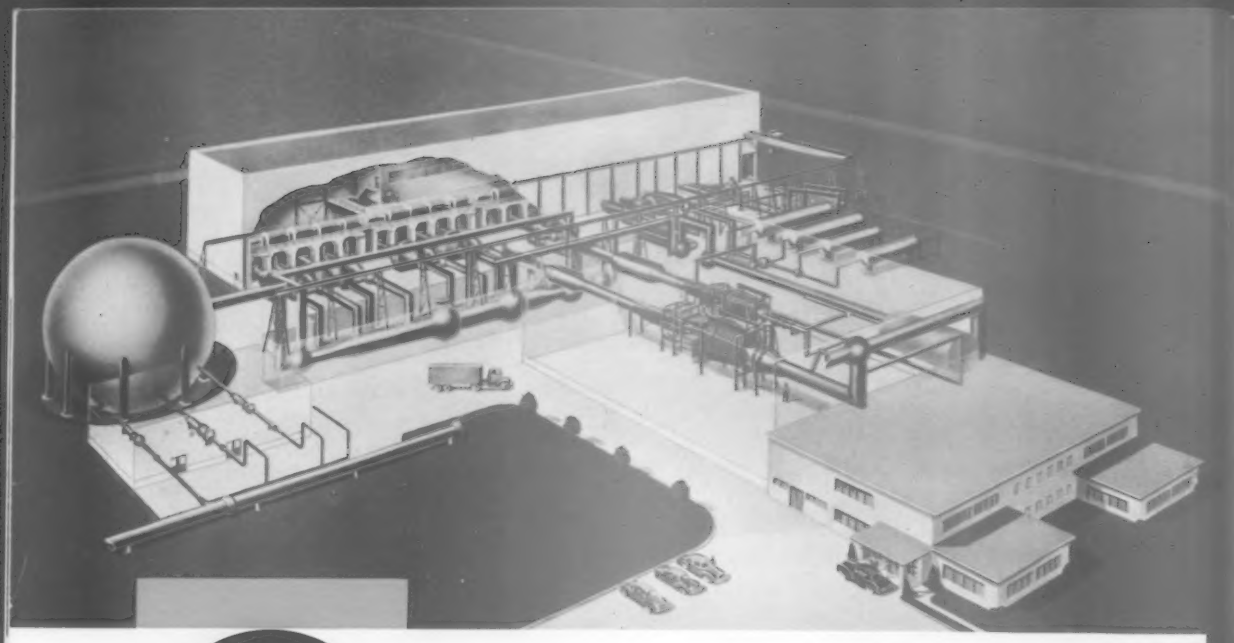
Samples of silicone rubber immersed in hot lubricating oil for a long period of time exhibit slight swelling and softening, but this is caused by absorption rather than chemical deterioration. Driving off the oil by further heating brings the rubber back to its original condition. Normal lubricating oil will have no significant effect on *Silco-Flex* insulated windings.

Solvents have the same effect on silicone rubber as lubricating oils, but to a greater or lesser degree, depending on the type of solvent. In general, prolonged contact with hydrocarbon-type solvents, such as gasoline, benzene, toluene, and xylene, as well as carbon tetrachloride and the highly aromatic oils, causes excessive swelling. Animal and vegetable oils, alcohols and ketones have little effect.

In addition, silicone rubber does not support fungus as do most organic materials. This property is of importance in very warm, damp locations where fungus growth is a problem, as in the tropics.

Silco-Flex silicone-rubber insulation is a definite improvement over conventional high temperature insulations made up of silicone-coated fabric and supported mica. Because of its resiliency, flexibility, homogeneous insulating wall and other qualities, *Silco-Flex* insulated equipment will have increased service life and reliability and will be less subject to the deteriorating influence of atmospheric or environmental conditions.

Even though *Silco-Flex* insulation is now available as a new and superior Class H material, probably of greater importance is its promise for the future. As larger quantities of the basic materials are used and as more production experience is gained, it could economically replace many conventional forms of coated fabric and supported mica insulation, decidedly increasing both life and service reliability of rotating electrical machinery. In addition, where motor enclosure applications are dictated by the limitations of conventional insulations, this new insulating system, with its superior resistance to moisture and environmental contaminants, may well modify present-day enclosure practices.



GDF WIND TUNNEL

For the World's Highest Air Speeds

by
C. F. CODRINGTON
Assistant to Manager
Blower and Condenser Dept.
and
M. F. GAY
Motor and Generator Dept.
Allis-Chalmers Mfg. Co.

In assuring America's future air supremacy, complex problems of high speed, high altitude flight will be answered in these wind tunnels.

WHEN PLACED IN FULL OPERATION, a series of wind tunnels for testing models at the highest air speeds ever developed in a continuous wind tunnel — called the Gas Dynamics Facility of the Arnold Engineering Development Center — will perform an important function in an overall research and development program conceived more than a decade ago.

During the early part of World War II, fundamental aerodynamic research was almost completely suspended.

THE GAS DYNAMICS FACILITY as conceived by an artist is shown with the main compressor building cut away exposing compressors. *(Drawing Courtesy AEDC)*

Almost without exception, facilities then existing were devoted to the more immediate problem of developing aircraft to win the war. This focused attention on the need for far more adequate facilities for testing and developing future aircraft and missiles. In addition, this expediency resulted in a postwar shortage of fundamental aerodynamic knowledge at a time when the rapid development of guided missiles, rockets, higher speed manned aircraft, and new types of power plants made this knowledge imperative.

In 1946 a plan to improve and augment aerodynamic research and development facilities was formulated. Included in this plan were specific wind tunnels to be built by the National Advisory Committee for Aerodynamics, the Navy, and the Air Force. The Arnold Engineering Development Center, often called simply AEDC, located about half way between Nashville and Chattanooga, Tennessee, is by far the largest single project in this overall program. The Gas Dynamics Facility is only one of three major facilities now being constructed at AEDC.

Dedicated to the memory of the late General H. H. Arnold, World War II commander of the Army Air Force, AEDC is a part of the U. S. Air Force's Air Research and Development Command. As its facilities are put into

operation, they will be made available to the other military services and to manufacturers of aircraft, engines, components, and missiles. Educational and research organizations engaged in propulsion and aerodynamic research or development may also participate in its use.

The three facilities being installed at the AEDC are: THE ENGINE TEST FACILITY (ETF), consisting of three test chambers devoted to research, development, and evaluation of turbojet, turboprop, and small ramjet engines. Flight conditions at altitudes to about 80,000 feet will be simulated and temperatures as low as minus 120 F will be reached.

THE PROPULSION WIND TUNNEL (PWT), which will actually consist of two large tunnels driven by a common power supply, one transonic, the other supersonic, each with a 16-foot-square test section. This facility is designed for developmental testing of full-scale operating ramjet and turbojet power plants installed in missiles and aircraft.

THE GAS DYNAMICS FACILITY (GDF), comprised of a group of supersonic and hypersonic wind tunnels which will be used for the developmental testing of models of aircraft, projectiles, and missiles designed to operate at extremely high speeds. The story of selecting compressors, drives, switchgear, and control for this facility is told on the following pages.

The most important feature of the Gas Dynamics Facility will be its ability to closely simulate, and possibly duplicate, full-scale missile flight. Designed for air speeds (Mach numbers, see Figure 1) higher than ever previously considered for tunnels this large, the Gas Dynamics Facility is intended for use in the gas dynamic region where air reaches speeds just below those at which slip flow occurs. Figure 2 defines Reynolds number, of importance in explaining this region, while Figures 3 and 4 define the gas dynamics region and indicate how these high air speeds are achieved.

Large compressor battery feeds continuous tests

GDF consists of three buildings and other equipment occupying an area approximately 400 by 500 feet. One of these buildings contains laboratory space, engineering offices, and two continuous flow tunnels each having test sections of 40 inches square cross section. Two smaller intermittent tunnels, each having a 12-inch-square cross section, are housed in a second building. The third building contains the main compressor battery of six axial and six centrifugal units, the 92,500 hp of required drive motors together with the necessary control and switchgear.

Projecting from this facility is a 720-foot-long high pressure storage bottle having a three-foot inside diameter. Pressurized air from this bottle feeds through either one of the 12-inch intermittent tunnels to a vacuum sphere 72.5 feet in diameter. The pressure bottle and vacuum sphere together provide the tremendous pressure ratio needed across the tunnel to reach high Mach numbers.

Since the pressure bottle and vacuum sphere can sustain high pressure ratios for a test of only a few seconds to

MACH NUMBER designates the ratio between the speed of a body and the speed of sound. Mach 1, the speed of sound, is about 760 mph at 60 F and at sea level, and varies proportionately with the square root of absolute temperature. Sound is audible evidence of disturbances or pressures being transmitted through the atmosphere. At speeds lower than Mach 1, pressure waves move out in advance of the object and prepare the air molecules for smooth flow around the object. When the object moves through the atmosphere at the same speed as the pressure wave or faster, the air molecules receive no advance warning and are displaced bodily, creating the characteristic shock wave. The areas of increased air density, resulting from shock waves, are clearly visible in the photo of a model during a supersonic test. **(FIGURE 1)**

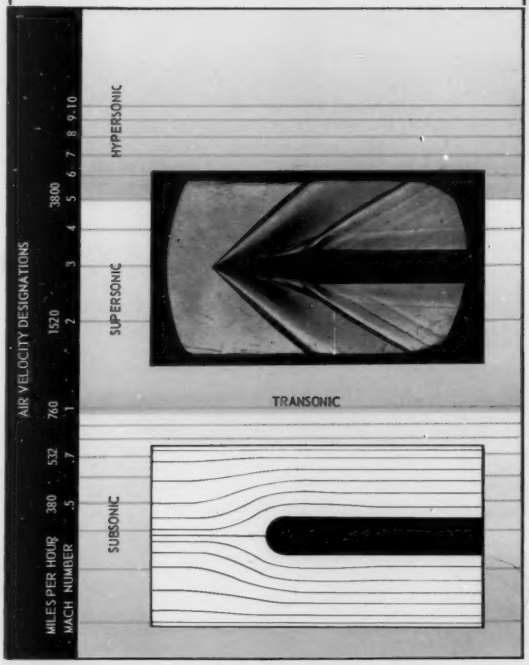


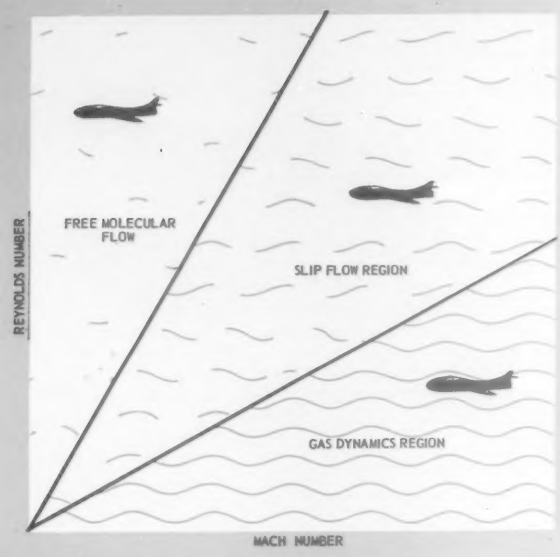
FIGURE 2

REYNOLDS NUMBER expresses the ratio between the dynamic forces and the viscous, or friction, forces in a fluid. Where the fluid is air, it is obtained by dividing the product of air density, air velocity, and a linear dimension of the body within or around the air by the coefficient of kinematic viscosity of the air:

$$R_e = \frac{\text{air density} \times \text{air velocity} \times \text{length of body}}{\text{kinematic coefficient of air viscosity}}$$

This ratio is an index of the general flow pattern within or around similar geometric structures.

When aircraft models are tested in a wind tunnel, Reynolds number indicates the extent to which actual forces on the actual aircraft in actual flight are simulated. Perfect simulation is achieved when the Reynolds number obtained on an exact scale model is the same as for the aircraft.



IN THE GAS DYNAMICS REGION, air is considered as a continuous fluid, like water in a pipe. In the Slip Flow region, definite gaps exist between air molecules, just as space exists between water particles in a spray and the molecules tend to slide on the body surface reducing the friction drag. In the Free Molecular Flow region, the space between successive molecules of air exceeds the length of the object moving through it. These phenomena are plotted as functions of Reynolds number and Mach number. **(FIG. 3)**

SUPERSONIC SPEEDS in a wind tunnel are obtained only by allowing air to expand as it passes from a constricted area, or throat, into an enlarged area. Until allowed to expand, Mach 1 is the maximum speed air can achieve regardless of the pressure applied.

The Mach number achieved by air particles is dependent directly upon two ratios between properties at the test section and at the throat. These ratios are the pressure ratio and the area ratio. Consequently, a means of controlling these ratios must be provided if more than one test speed is to be attained. Pressure ratio is of importance only in establishing supersonic flow. For a given tunnel configuration, there is a critical pressure ratio below which supersonic flow cannot be established. Above this critical pressure ratio, the area ratio (the ratio of the test section area to the throat area) is the only factor which determines the Mach number in the test section. Area ratio can be varied by an adjustable throat, such as the one shown, or by separate nozzles for each specific speed. **(FIGURE 4)**

perhaps several minutes' duration, they are of no value when continuous test runs are required. Consequently, the 40-inch-square supersonic and hypersonic wind tunnels will depend on the main battery of compressors and exhausters to maintain the pressure ratios necessary for continuous testing.

Preliminary studies of the requirements for the main compressor battery and drive units at GDF were started late in 1946. Every facet of the overall problem was exhaustively investigated to assure a final installation that would give the maximum possible performance and flexibility. Equipment already developed and commercially available was carefully studied in an effort to select equipment of proven dependability. During the period of engineering studies and discussions, because of the rapid progress being made and anticipated in the aerodynamic designs of aircraft and missiles, numerous re-evaluations were necessary to assure that the facility would be capable of exceeding projected development requirements.

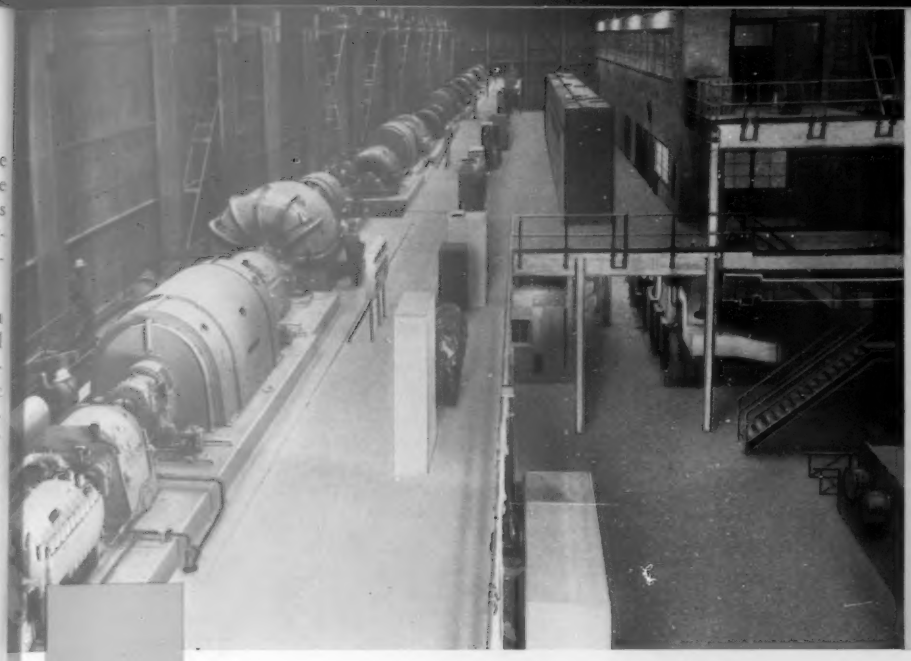
Selecting main compressor battery equipment

In selecting equipment for the main compressor battery, Mach number and Reynolds number were of vital concern. At the same time, the horsepower required to drive each of the various systems considered was carefully reviewed to assure that both installed horsepower and operating horsepower would be kept to a minimum. Wherever possible, existing designs were given preference. In this way any extensive development program on the compressor and drive system prior to manufacture was eliminated. Also, the probability of modifications after the equipment is in service is substantially reduced.

Selecting equipment to develop and sustain suitable pressures and volumes of air for GDF's continuous test runs resolved into three distinct problems: (1) proper selection of compressors and exhausters, (2) selection and design of compressor drive units, (3) design of control circuits for the drives and selection of appropriate control and switchgear components.

A FULL COLOR PICTURE of the Gas Dynamics Facility appears on pages 18 and 19. Articles through page 24 are devoted to the selecting, designing and arranging of compressors, drive motors, switchgear and control for this facility.

The authors and editors are grateful to Air Force and ARO personnel at the Arnold Engineering Development Center for the information they supplied and for their help in describing the Gas Dynamics Region . . . and to Merrill A. Mader, Superintendent of Installation for Allis-Chalmers equipment at AEDC, for his assistance and cooperation.



A COMPRESSION RATIO of 2500 to 1 is obtained from this compressor system located within one of the Gas Dynamics Facility buildings.

GDF

Compressor Selection and Arrangement

by **C. F. CODRINGTON**
Assistant to Manager
Blower and Condenser Department
Allis-Chalmers Mfg. Co.

COMBINING THE HIGHEST MACH NUMBERS ever considered for a closed-loop tunnel with high Reynolds numbers will give test data easily convertible to actual flight conditions. While this combination will permit close simulation and possible duplication of full-scale missile flight, it made the compressor selection problem a difficult one.

Engineering discussions to determine the air volumes, inlet pressures, pressure ratios, flow conditions, and horsepower requirements started approximately four years before any specifications were issued. During these discussions, consideration had to be given to Mach number and Reynolds number effect on compressor design.

At one time, an extremely low inlet pressure to the first stage (approximately 0.075 psia) was considered in order to save horsepower. However, insufficient operating experience at the low Reynolds numbers that would result from this low inlet pressure might entail an extensive compressor design and development program. Consequently, an inlet pressure of approximately 1.0 psia was selected. This selection of inlet pressure, together with output pressure and volume specifications, established inlet volume and overall pressure ratio.

Compression ratio is 2500 to 1

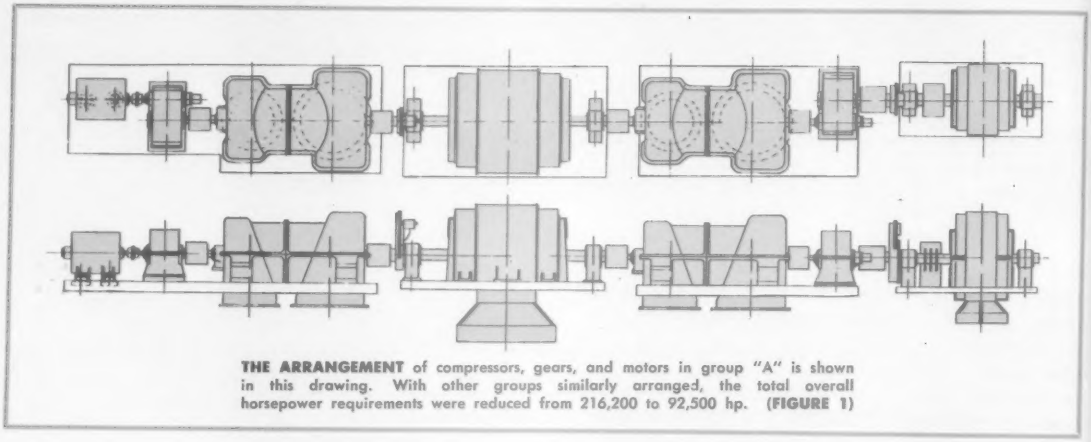
Final inlet requirements for the maximum conditions were set at a volume of 600,000 cfm with an inlet pressure of 1 psia. Discharge pressure was specified at 2500 psia. In addition to these maximum conditions, operating conditions were specified for reduced volumes and pressure ratios, and various inlet pressures.

Stage of Compression	Number of Units	Capacity of each (cfm)	Compression Ratio	Max. Discharge Pressure (psia)	Maximum hp — each
1	4	150,000	3.08/1.0	67	22,800
2	2	125,000	3.08/1.0	80	22,800
3	1	91,000	3.08/1.0	110	22,600
4	1	32,500	2.64/1.0	195	14,300
5	1	13,000	2.64/1.0	500	14,200
6	1	5,200	2.5/1.0	780	10,400
7	1	2,320	2.2/1.0	1600	9,700
8	1	1,160	2.2/1.0	2500	8,200

TABLE I

Compressor Group Designation	Number and Stage of Compressors in Group	
A	2 — 1st stage	and 1 — 7th stage
B	2 — 1st	and 1 — 8th
C	1 — 2nd	and 1 — 4th
D	1 — 2nd	and 1 — 5th
E	1 — 3rd	and 1 — 6th

TABLE II



THE ARRANGEMENT of compressors, gears, and motors in group "A" is shown in this drawing. With other groups similarly arranged, the total overall horsepower requirements were reduced from 216,200 to 92,500 hp. **(FIGURE 1)**

To meet the 2500 to 1 compression ratio of the system while allowing for the intercooler and interconnecting losses, eight compressors operating in series were required. After deciding on this arrangement, the volume per step of compression was determined.

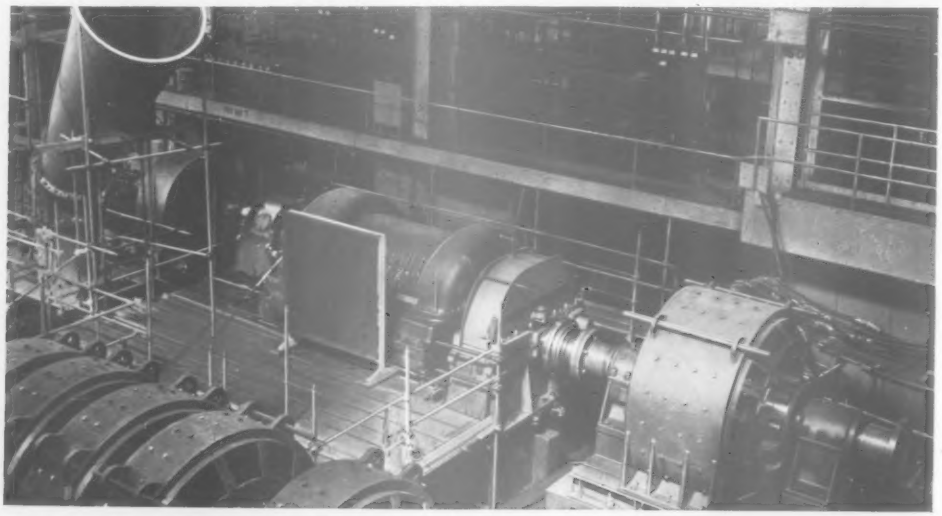
Since the 600,000-cfm maximum inlet volume would not be required for all tests, increased system flexibility was obtained by paralleling compressors in each of the first two compression steps. Four 150,000-cfm axial compressors operating in parallel, each with a design compression ratio of 3.08/1.0, were selected for the first step. For the second step of compression, two 125,000-cfm axial compressors with the same compression ratio were paralleled. For the subsequent steps of compression, multistage centrifugal compressors were used. The final and complete selection of compressors used for this project is shown in Table I. The compressors selected assured maximum flexibility to meet the wide range of operating conditions.

Arrangement halves required horsepower

Table I indicates that if separate drives had been used for each compressor, the total installed horsepower would have been 216,000. By correct grouping of compressors, the total installed horsepower was cut to only 92,500.

Many different combinations of compressors were considered in selecting the drive finally used. Various combinations were compared for equipment cost, total installed horsepower requirements, and the number of drives in operation for each operating condition. The arrangement selected requires five identical drives with a total installed horsepower of only 92,500. Each drive is capable of handling a maximum of approximately 23,125 horsepower when operating at the 25 percent overload rating. It is not necessary that all the drives be operating for every operating condition.

When only the first stage of compression is required, higher inlet pressures can be used. Later stages can be



SIX AXIAL COMPRESSORS, identical except for blade-angle setting, were used. Four in series or parallel comprise the first stage, two in series or parallel, the the second stage. For future reference, shop tests were conducted with several different blade-angle settings. **(FIGURE 2)**

either disconnected or idled on the line. When higher stages are required, inlet pressures to the first stages are lowered. In this way the horsepower required for earlier stages is reduced, and additional installed horsepower is made available for higher stages.

Figure 1 shows the general arrangement of one group of equipment. Each of the other four groups has a similar arrangement.

Dry air a must

In addition to the complicated performance requirements of this compressor system, several other special requirements were imposed. To prevent condensation and possible mechanical damage within the wind tunnel during high velocity tests, air in the system had to be kept absolutely dry and clean. To assure clean, dry, oil-free air in the test sections, inleakage and outleakage specifications for the compressor system were extremely stringent.

Maximum inleakage on any compressor that may have to operate at an inlet pressure below atmospheric pressure was limited to approximately 3.0 pounds per minute. Outleakage from the system had to be kept at a minimum to reduce the need for make-up of dry air. To assure minimum leakage, all casings and joints are very tight. In addition, the seals between rotating and nonrotating compressor parts were given special consideration.

Each compressor was equipped with dry-type shaft seals wherever air might possibly leak in or out. For the first three stages of compression, shaft seals on the compressors consisted of a rotating shoulder and a nonrotating seal ring suspended in a nose-piece assembly. The rotating seal shoulder is made of steel, and the stationary seal ring face is made of special grade carbon. The subsequent compressors have similar contact seals and, in addition, labyrinth seals. Where the two seals are used, they are interconnected to an intermediate point by bleed lines. This maintains the pressure differential across the contact seal below a predetermined maximum limit. On tests, this seal arrangement has exceeded specification requirements by ample margins.

A special feature of the axial compressor design is the method of blade fastening. Blades for the axial compressors were designed to permit several different blade settings. Because of this, identical units could be used for both first and second-stage compressors by merely changing blade angle. One of these compressors is shown during shop testing in Figure 2.

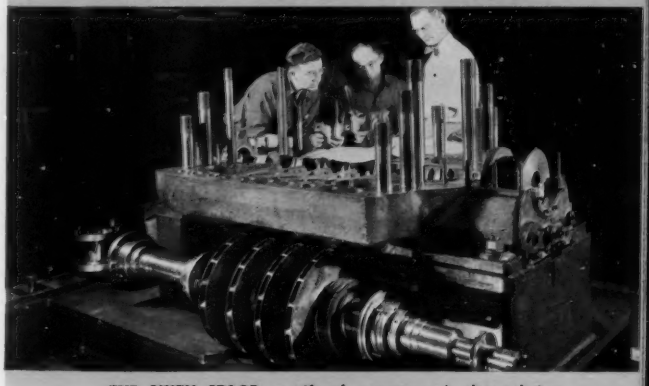
All third to sixth-stage compressors are four-impeller centrifugal-type units with horizontally split casings. The lower half casing and rotor of the sixth-stage unit are shown in Figure 3.

The seventh and eighth-stage centrifugal compressors are vertically split barrel units with inlet and discharge nozzles integrally cast with the casings. Casing heads are bolted to the casings on the inlet side. Each unit required three impellers in order to obtain designed pressure ratio. The eighth-stage unit was given a hydrostatic test at 3800 psia, 1300 psia in excess of the 2500 psia for which it was designed. Figures 4 and 5 show shop views of the eighth-stage compressors.

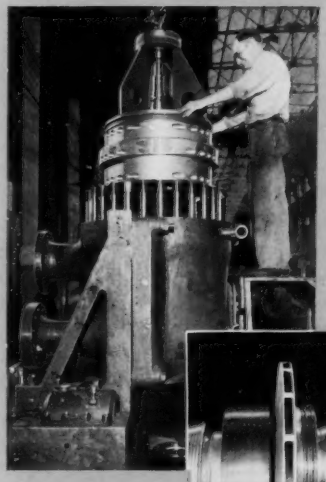
For the first three steps of compression, compressor casings were made of high test cast iron. For the last five steps, compressor casings were made of cast steel.

In the preferred method for placing the compressor battery in operation, each compressor is started as an exhauster to lower the pressure in the system, reducing the required horsepower.

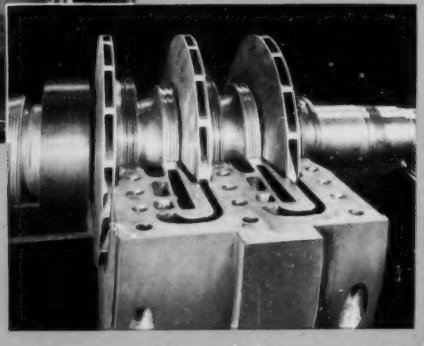
Tests that have been conducted indicate that this compressor arrangement, requiring only 92,500 horsepower of installed driving equipment instead of the 216,000 horsepower that had been considered earlier, will meet and exceed maximum requirements.



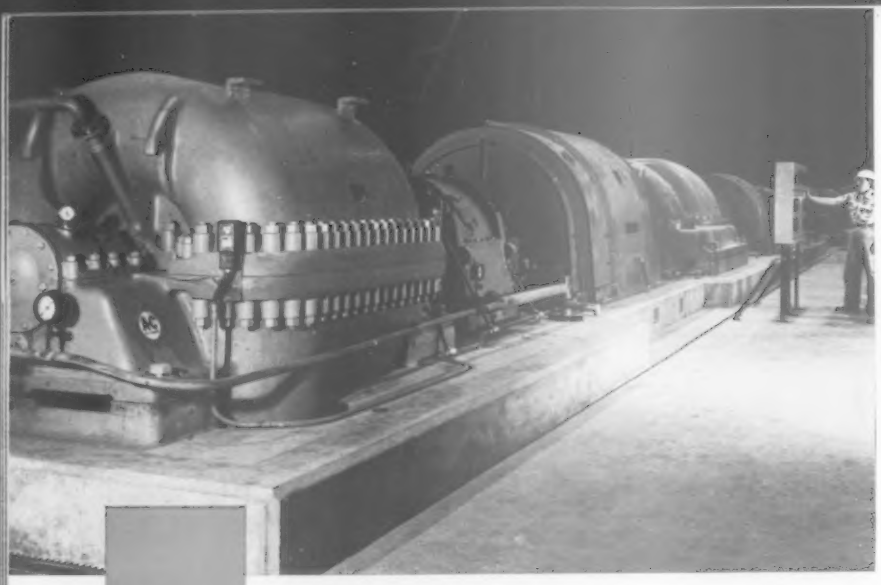
THE SIXTH STAGE centrifugal compressor is shown being readied for shop testing. Rated 5200 cfm, 2.5 to 1 compression ratio, its horizontal split casing and four-impeller rotor are typical of all third to sixth-stage compressors. **(FIG. 3)**



INLET AND DISCHARGE nozzles are integrally cast on the eighth-stage compressor, which has a discharge pressure of 2500 psia. **(FIGURE 4)**



ROTOR and diffuser details are identical for the seventh and eighth-stage compressors. **(FIG. 5)**



EACH OF FIVE compressor groups is driven by a 16,000-hp, 3600-rpm main-drive synchronous motor and a 2500-hp, wound-rotor starting motor. **(FIG. 6)**

GDF

Drive Selection

by M. F. GAY
Motor and Generator Department
Allis-Chalmers Mfg. Co.

THE COMPRESSOR ARRANGEMENT finally selected has five drive units. All five have identical main-drive motors. Although dividing the total load into five equal increments presented many problems, numerous economies and operating advantages were achieved by this arrangement. Economies resulted from reduced spare parts requirements and from the simplification of design, manufacture, and installation procedures.

In addition, this duplication of equipment was conducive to simplified operating, maintenance, and inspection procedures. Under emergency conditions, operating personnel will be able to take positive remedial action more rapidly than might otherwise be possible.

Each of the five main-drive motors is a 16,000-hp, 2-pole, 3600-rpm, 6600-volt, unity power factor totally enclosed synchronous motor. This speed permitted direct connection of main-drive motors to the 3600-rpm compressors, as shown in Figure 7. The use of synchronous motors and power-factor regulators was dictated by a desire to keep kva requirements as low as possible.

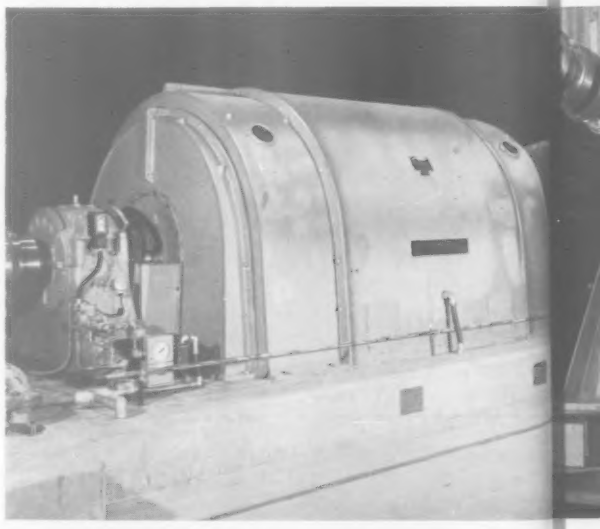
Arranged for recirculating ventilation, each motor has an air-to-water heat exchanger located beneath it. Fans on the motor rotor circulate air through the motor, into a duct below the motor, through the cooler, into a plenum chamber below the motor, and back into the motor end. This arrangement eliminates the discharge of motor heat losses into the motor room. It also assures maximum protection from foreign materials that might otherwise be drawn into the motor and damage the insulation.

To ease starting, each drive motor was provided with a high pressure lubricating system to force oil under each of the two bearings during the starting period. Breakaway torque is reduced to a very low value, and adequate lubrication to the bearings during the first few revolutions is assured by this system.

Other protective features furnished with these motors include: resistance-type stator temperature detectors, space heaters, hand-reset bearing temperature relays, bearing temperature thermocouples, differential protective devices, and pilot brushes to measure field resistance for rotor field temperature indication. Current transformers were mounted in the neutral connection in the terminal box at the bottom of each motor.

Unique rotor removal procedure

Since there are compressors on both ends of each main-drive motor, rotors cannot be removed or installed while stators are in place. A unique method of rotor removal was provided to permit servicing the installed equipment



MAIN-DRIVE MOTORS drive from both ends of the rotor shaft and are close-coupled to adjacent equipment. **(FIGURE 7)**

without removing the drive motors from their installed locations.

Drive motors are designed for rotor removal after the motor has been jacked into a tilted position similar to that shown in Figure 8. Suitable rollers for the stator bore, jacks, hinges, and supports were provided for each motor. After tilting, the rotor can be removed from the stator over the top of one of the compressors it normally drives. In this way main-drive motors can be serviced without disturbing adjacent equipment or removing the complete motor to a service area.

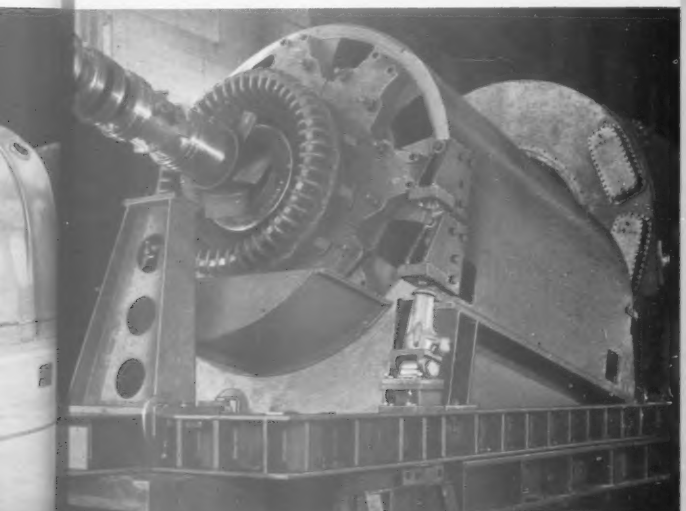
With this rotor removal method, diagrammed in Figure 9, crane capacity need be sufficient to lift only one-half of the weight of the rotor and stator. This type of rotor removal not only reduced the size of the crane required for handling the equipment, but also substantially reduced the structural requirements of the building that supports the crane.

Each drive has its own starting motor

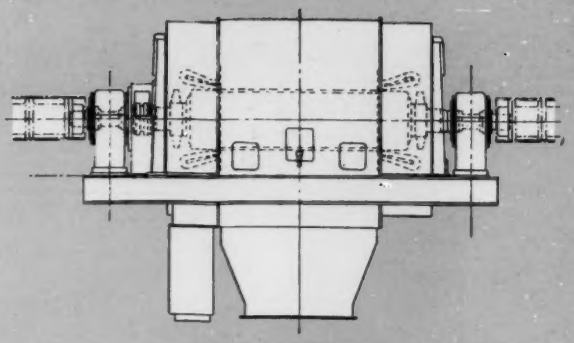
Because of high connected inertia and restrictions on starting kva, the synchronous main-drive motors are accelerated with wound-rotor starting motors. The starting motors were sized to accelerate the complete drive unit within a predetermined period of time. Each of the five starting motors, rated 2500 hp, 6600 volts, 1185 rpm, has a 25 percent overload capacity for two hours, and a 200 percent short-time torque rating.

While accelerating the main drive, each starting motor is controlled by a liquid rheostat. Mechanically connected through gear units, starting motors develop suitable torque at 1123.8-rpm operating speed to permit synchronizing the main-drive motors to the line.

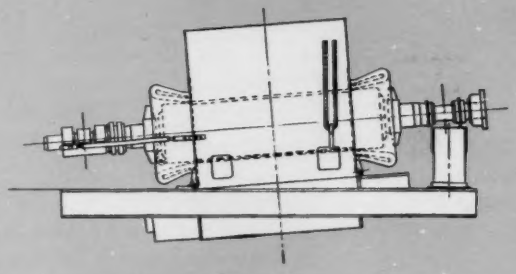
Like the main-drive synchronous motors, starting motors have totally enclosed, recirculating ventilation systems. In addition, they have motor-driven blowers for circulating



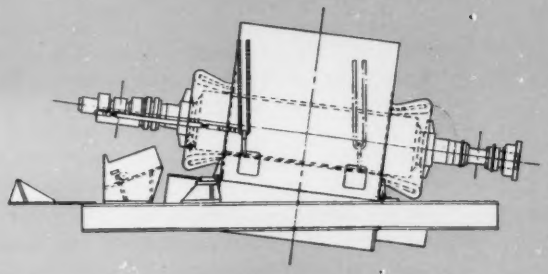
ROTOR REMOVAL, without removing the motor to a service area, is accomplished after the motor is in a tilted position. **(FIGURE 8)**



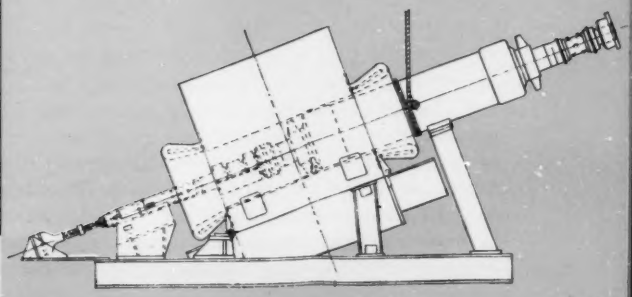
TO REMOVE ROTOR, upper bearing caps, and other mechanical and electrical parts that would interfere with motor jacking, are removed.



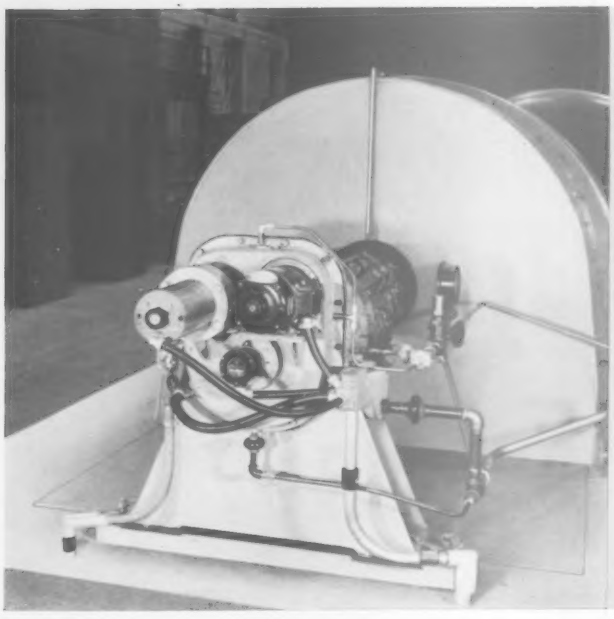
MOTOR IS RAISED as shown, first one side then the other, until shaft clears bearing pedestal. Pedestal is then removed.



WITH ROTOR IN PLACE, motor is tilted as shown and yoke hinges are placed in position.



PIVOTED ON YOKE HINGES, the motor is next tilted into position for rotor removal across the rotor saddle and over the top of the adjacent machine. **(FIGURE 9)**



EACH 2500-HP WOUND-ROTOR starting motor has a tachometer generator, zero speed switch and reversing switch attached to the commutator end. These devices assure proper starting and initiate control functions during acceleration to operating speed. **(FIGURE 10)**

air through ducts, coolers, motors, and plenum chambers. Forced-air cooling is necessary because of the large amount of heat developed in the starting motors during acceleration.

In general, the same type of protective devices were installed for the starting motors as for the main-drive motors.

Starting the compressor drive

Drive units can be started automatically, manually, or semi-automatically. All of the auxiliaries, including an auxiliary compressor used to establish proper pressure level within the compressor and connected piping, are started first. After proper pressure level has been established in the compressor, the main breaker to the wound-rotor starting motor is closed.

During automatic acceleration, automatic torque control brings the wound-rotor starting motor up to speed. A suitable control circuit, incorporating a rotating regulator, positions the electrodes of a liquid rheostat to maintain the desired torque output. Acceleration is set for 100 percent torque until half speed is reached. Then a tachometer generator speed signal operates a relay, and control is transferred from 100 to 200 percent wound-rotor motor torque output. The tachometer generator and starting motor are shown in Figure 10.

At approximately 98 percent speed, the tachometer generator speed signal again operates a relay, and control of the wound-rotor motor is transferred from torque control to the control of a *Synchro-Operator*. This device sends a signal back to the liquid rheostat to either increase or decrease the speed of the wound-rotor starting motor. The *Synchro-Operator* compares the frequency of the synchronous motor with the line frequency, checks phase angle, and initiates breaker closing at the proper instant. After connecting the main-drive motor to the power supply, the *Synchro-Operator* becomes inoperative.

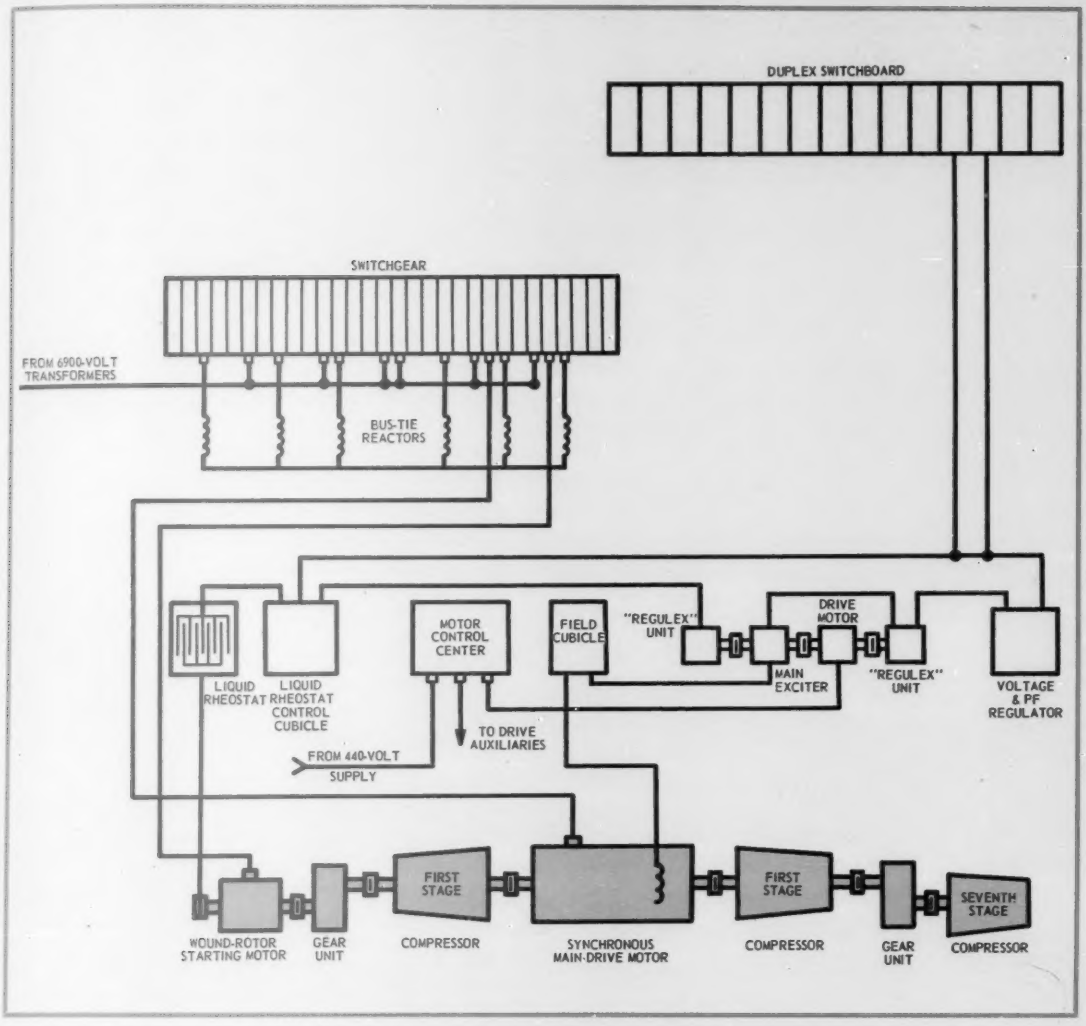
This entire accelerating and synchronizing procedure is accomplished automatically. The synchronous main-drive motors are connected to the line with very little interchange of kva between the power supply and the synchronous machines. While only the automatic method has been explained, provisions are incorporated to permit selection of manual or semi-automatic control of the accelerating and synchronizing procedures.

Auxiliaries and their functions

A separate motor-generator set was supplied for each of the five drive units. In addition to its drive motor, each motor-generator set has a main exciter for supplying excitation of the synchronous motor, one *Regulex* generator for controlling the electrode-position motor on the liquid rheostat, and a second *Regulex* generator for controlling excitation to the main synchronous motor exciter.

The main exciter is rated 50 kw at 250 volts. The *Regulex* generator supplying its excitation is rated 5 kw at 250 volts, and is controlled by a combination voltage and power-factor regulator.

When starting, excitation is not applied to the synchronous main-drive motor until it reaches approximately 98 percent speed. Prior to synchronization, excitation is regulated by a voltage regulator incorporating rotating amplifiers to match the voltage of the synchronous motor with the voltage of the power supply. After synchronization, control is transferred to power-factor regulation. The



FUNCTIONS of various equipment and auxiliaries during drive acceleration can be traced on this combined simplified single line and block diagram. **(FIGURE 11)**

regulator, together with the *Regulex* exciter and the main exciter, then controls excitation to the synchronous motor and maintains rated power factor at the synchronous motor terminals.

Torque output of the wound-rotor starting motor is controlled during acceleration by the liquid rheostat electrodes' position, which in turn is controlled by the *Regulex* set. Torque control is arranged for 100 percent starting motor torque from standstill to 50 percent speed. At 50 percent speed, control is transferred to increase output to 200 percent rated torque. At approximately 98 percent speed, control is transferred to the *Synchro-Operator*.

From then until synchronization has been completed, the *Synchro-Operator* provides a signal either increasing or decreasing speed to match the synchronous motor output voltage frequency and phase angle to the line frequency and phase angle.

All of the control switching, metering, and relaying devices necessary for the control, protection, and observation of each of the five drive units are centralized on a duplex tunnel-type board. Starters for all of the miscellaneous auxiliaries, such as pumps, m-g sets, emergency lighting, space and lube oil heaters, are grouped in a control center.

Extensive acceptance tests are now in process at GDF, and a program for the progressive utilization of its test facilities has already been planned. Experience to date indicates that this will be a very successful aerodynamic test facility, fully capable of sustaining the high Mach numbers for which it was designed.

WORLD'S HIGHEST AIR SPEEDS will be developed in wind tunnels of the Gas Dynamics Facility. *(Photo Courtesy AEDC)*

CONTROL BOARD and switchgear for the Gas Dynamics Facility compressor drives.

GDF

POWER DISTRIBUTION AND CONTROL

by **JOHN BAUDE**
and
HEINZ BUSS
Switchgear Department
Allis-Chalmers Mfg. Co.

ALTHOUGH COMBINING the highest Mach numbers with the highest Reynolds numbers ever considered for a tunnel its size, the Gas Dynamics Facility is not an exceptional installation when its horsepower requirements are compared with a few other installations. However, the particular solution to the complex operational problems of this 92,500-hp compressor drive is of interest because the value of the installed machinery hinges on the precision, accuracy, and protection provided by its control. In this installation the control problems were solved by coordinating and simplifying the various functions.

Power distribution is first problem

Figure 1 shows, in simplified form, the flow of power from the power source through three double-secondary power transformers to five 18,500-hp compressor drive systems and their auxiliary power equipment. This somewhat unconventional illustration emphasizes the logic behind the arrangement of the main power distribution system layout.

The power is taken from the 154-kv system and fed through three 33,333-kva double-secondary power transformers into a six-section 6.9-kv bus system from which the five 16,000-hp synchronous main-drive motors and five 2500-hp wound-rotor motors draw their power. Various auxiliary supply lines provide additional power. The system's short circuit capacity is reduced by introducing six 715-kva, 199-volt, 1200-ampere, 5 percent reactors, connected in two groups of three each to a common bus. Each group is grounded by a 6.9-kv, 2.4-ohm zigzag-wound grounding transformer and a 2.5-ohm grounding resistor. With this layout, circuit breaker capacity could be reduced to 500 mva. Breakers are mounted in metal-clad switchgear shown above and in Figure 2.

Relatively even distribution of power from the six secondary windings of the three power transformers is obtained by symmetrically interlacing the distribution system. Each of five secondary windings of the transformers feeds one 16,000-hp synchronous motor, while each of the five wound-rotor starting motors is connected to a different bus section. The sixth secondary winding, designated secondary II of transformer 3 in Figure 1, feeds the starting motor of one drive and supplies power to wind-tunnel heaters through feeder *A*. Secondary I of transformer 1 has no starting motor load. Instead, it supplies feeder *B*, an auxiliary feeder for the entire facility.

Continuity of service, of special importance in this installation because of the aerodynamic difficulties and shock waves associated with sudden deceleration from high air speeds, was a major consideration in selecting this distribution system. Its interlaced bus sections promote even distribution of load among the windings of the three power transformers. After this distribution system arrangement

was selected, relaying, metering, and control devices were chosen to coordinate with the basic functions of the primary distribution system.

Protective relaying and metering

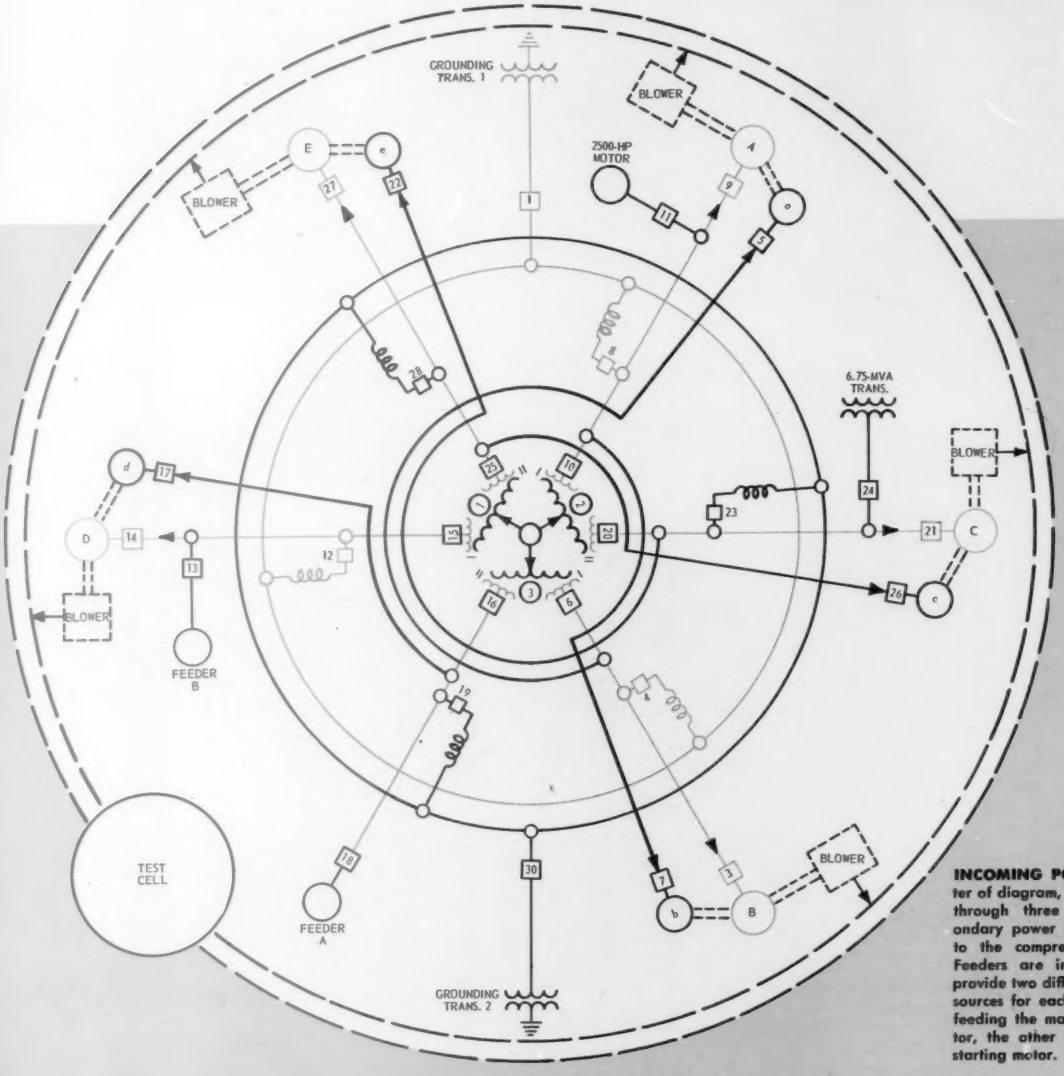
A list of the various protective relays and meters is shown in Table I. In designing the circuit, special effort was made to prevent overlapping of relay response. The circuit assures delay in shutdown until after corrective measures can be undertaken, which will prevent damage to any equipment under test in the wind tunnel. Time delays were introduced where necessary to assure the safety of operating personnel and test equipment.

The point from which all control functions emanate is the 50-foot-long main control switchboard pictured in Figure 3. It is the electrical nerve center of the entire facility and is shown in Figure 4 as a focal double ring. All functions originate from this ring. For convenience, they are divided into two major categories. Category I, inside the ring, includes all functions pertaining to power supply. Category II, external to the ring, includes all the control functions for the five electrical compressor drives, designated "A," "B," "C," "D," and "E."

In Category I, the key points to be controlled are the six incoming line breakers, one for each of the two secondaries of the three power transformers. Each of these breakers may be closed or tripped by an operator, provided the main load dispatcher approves. Automatic tripping is also provided for system protection. It is used in the synchronous drive motor, ground transformer, and power transformer circuits. All other breakers in the power supply group are similarly controlled.

Since a time delay between the initiation and execution of tripping action was necessary for equipment protection, trouble contacts from as many as a dozen or more sources were combined in one single timing relay circuit rather than in a multitude of individual timers.

Associated with each of the six incoming line breakers are six devices, called thermal converters, which signal the total load quantity into a totalizing load recorder. Another recorder is tied in electronically with the totalizing recorder



INCOMING POWER, center of diagram, radiates out through three double-secondary power transformers to the compressor drives. Feeders are interlaced to provide two different power sources for each drive, one feeding the main-drive motor, the other feeding the starting motor. **(FIGURE 1)**

to automatically compute the total load change increment or decrement per minute. In case this value exceeds a fixed maximum determined by power system requirements, a general warning alarm is initiated.

A power supply system annunciator is provided as the last functional component of Category I. In its design, special attention was given to assure that false alarms will be avoided. An impending rapid shutdown of the installation is to be signaled only in extreme emergencies. The annunciator is arranged to initiate two types of visual alarms — either a red danger signal, or an amber warning signal — both coinciding with a common audible alarm.

Red danger alarms, forewarning impending shutdowns, are caused by main power source difficulties, primary supply faults, and the like.

Amber warning alarms announce impending dangers requiring investigation. This type of alarm may signal a transient fault or may be followed by a danger alarm. Warning alarms generally announce fault conditions that may be cleared quickly enough to avoid serious trouble and shutdown.

Starting procedure

The inner circle components of Figure 4, although important, are somewhat simpler than the electric drive control in Category II. Since the major functions apply identically to all five drives, the 10 subdivisions of the functions, given below and indicated at the top center of Figure 4, apply for all five drives.

1. Start of essential drive auxiliaries by one central master switch.

2. Further starting preparations are dependent upon a certain number of prerequisites which, if existent, release a main switchboard approval light signal and set up the closing circuits of the wound-rotor motor breaker.

3. Synchronizing selection is the next step. Three choices are available by means of setting a switchboard master synchronizing switch in either:

(*a*) *Auto position* for automatic acceleration of wound-rotor and automatic synchronizing of the main-drive motor.

(*b*) *Semi-automatic position* for manual acceleration of wound-rotor motor and automatic synchronizing of the main-drive motor.

(*c*) *Manual position* for manual acceleration of wound-rotor motor and manual synchronizing of the main-drive motor by means of voltmeter, synchroscope, and synchronizing lamps.

4. Voltage and power-factor regulator is brought into play.

5. Main exciter voltage is checked and adjusted, concluding actual starting preparations.

6. The wound-rotor motor is subsequently set in motion.

7. Simultaneously a starting sequence timing relay is energized. Its function is to monitor the time lapse between the closing of the wound-rotor motor breaker and

TABLE I

PROTECTION										METERING								
Unit	Designation	51/50 Overcurrent	51G Ground	51GA Grd. Alarm	87 Differential	46 Current Bal.	49 Thermal Overcurr.	51A Overcurr. Alarm	47 Undervoltage	Unit	Designation	Voltmeter	Ammeter	Wattmeter	PF Meter	Var. Meter	Watt-Hour Meter	Totalizing Recorder
1	Grd. Transformer	X	X	X						3	Syn. Motor "B"	X	X	X	X			
3	Syn. Motor "B"	X	X		X	X	X			4	Reactor Unit		X	X		X		
5	Ind. Motor "A"	X	X		X	X	X	X		5	Ind. Motor "A"		X	X				
6	Trans. 3 — Inc. Line	X			X				X	6	Trans. 3 — Inc. Line		X	X		X	X	X
7	Ind. Motor "B"	X	X		X	X	X	X		7	Ind. Motor "B"		X	X				
9	Syn. Motor "A"	X	X		X	X	X			8	Reactor Unit		X	X		X		
10	Trans. 2 — Inc. Line	X			X				X	9	Syn. Motor "A"	X	X	X	X			
11	Aux. Compr. Ind. Motor	X	X			X	X			10	Trans. 2 — Inc. Line		X	X		X	X	X
13	Feeder "B"	X	X							11	Aux. Compr. Ind. Motor	Remote Metering						
14	Syn. Motor "D"	X	X		X	X	X			12	Reactor Unit		X	X		X		
15	Trans. 1 — Inc. Line	X			X				X	13	Feeder "B"		X					
16	Trans. 3 — Inc. Line	X			X				X	14	Syn. Motor "D"	X	X	X	X			
17	Ind. Motor "D"	X	X		X	X	X	X		15	Trans. 1 — Inc. Line		X	X		X	X	X
18	Feeder "A"	X	X							16	Trans. 3 — Inc. Line		X	X		X	X	X
20	Trans. 2 — Inc. Line	X			X				X	17	Ind. Motor "D"		X	X				
21	Syn. Motor "C"	X	X		X	X	X			18	Feeder "A"		X					
22	Ind. Motor "E"	X	X		X	X	X	X		19	Reactor Unit		X	X		X		
24	6.75-mva Trans.	X	X							20	Trans. 2 — Inc. Line		X	X		X	X	X
25	Trans. 1 — Inc. Line	X			X				X	21	Syn. Motor "C"	X	X	X	X			
26	Ind. Motor "C"	X	X		X	X	X	X		22	Ind. Motor "E"		X	X				
27	Syn. Motor "E"	X	X		X	X	X			23	Reactor Unit		X	X		X		
30	Grd. Transformer	X	X	X						24	6.75-mva Trans.	Remote Metering						
										25	Trans. 1 — Inc. Line		X	X		X	X	X
										26	Ind. Motor "C"		X	X				
										27	Syn. Motor "E"	X	X	X	X			
										28	Reactor Unit		X	X		X		

the moment the synchronous main-drive motor is placed on the line. In case this time interval exceeds a predetermined value, the wound-rotor motor breaker is instantaneously tripped. The starting procedure is repeated after checking and eliminating the trouble source.

8. The wound-rotor motor is accelerated at 100 percent torque up to 50 percent synchronous speed by means of a liquid rheostat, then at 200 percent torque up to about 98 percent synchronous speed. Acceleration is either manually or automatically controlled, depending upon the method selected in step 3. At approximately 98 percent synchronous speed, the *Synchro-Operator* automatically assumes control over wound-rotor motor speed and the voltage power-factor regulator, unless manual synchronization was chosen.

9. At 98 percent synchronous speed, the synchronous motor field is applied automatically or manually, depending upon method selected in step 3.

10. At the moment synchronism is reached, the main-drive motor breaker is closed either automatically by a *Synchro-Operator* contact, or manually by a switchboard control switch closing contact, depending upon the presetting. The drive is now on the line.

Other main drives are started in the same manner according to this fixed sequence if more than one main drive is required to meet the aerodynamic requirements of the tests to be conducted.

Normal manual shutdown of the drives is also performed in a definite sequence of control operations and time intervals. The wound-rotor motor may be tripped off the line while the drive is in operation if the total load does not exceed the synchronous motor rating. Conversely, the wound-rotor motor may be restarted while the drive is operating, in order to support the synchronous motor should it become overloaded. Starting approval interlocks are automatically by-passed if the wound-rotor motor is restarted while the synchronous motor is on the line.

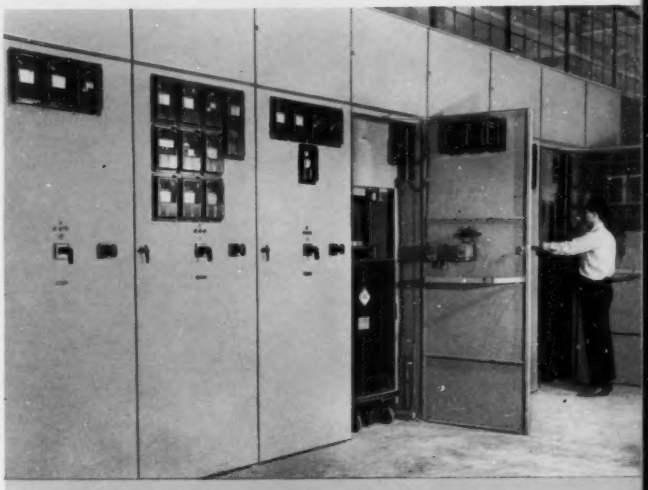
Normal manual shutdown is accomplished in three simple steps. These steps are initiated by operating control switches that (1) open the synchronous motor breaker and remove motor field excitation, (2) open the wound-rotor motor breaker (unless already tripped), and (3) trip all drive auxiliaries. During this control function the proper rate of total drive load decrement must be maintained for power system stability reasons.

Emergency shutdown of any drive will be used only in extreme cases, and then only as a last resort. Operating a single pushbutton releases a danger alarm and simultaneously initiates a time-delay trip of the synchronous main-drive motor breaker, its field breaker, and its wound-rotor starting motor breaker. The time delay is set at the minimum permissible to avoid major damages to the wind tunnel.

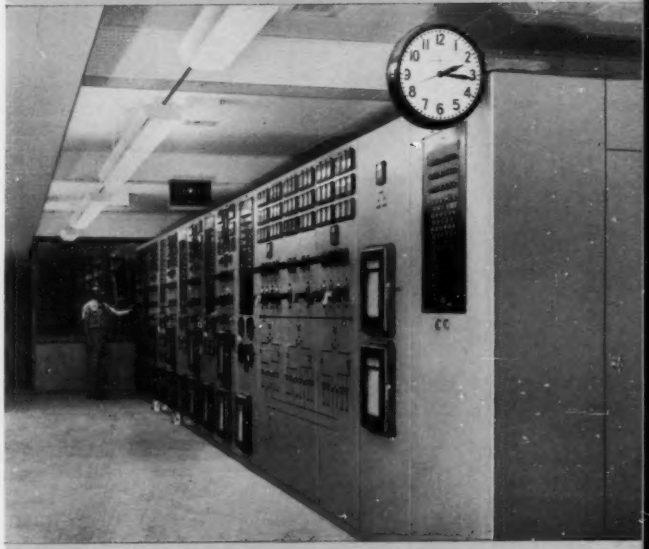
Automatic trip and lockout functions for the synchronous main-drive motors and wound-rotor motors are basically the same as those applied to the power supply breakers and include centralized time-delay action. Complex detail groups are centralized and combined toward a simple, definite end result — namely, protection of the electrical and mechanical parts of the wind tunnel.

One trouble annunciator per drive, similar in design to its power supply system counterpart, gives both visual and audible signals. Red danger alarms and amber warnings issue from it in case of overspeed, synchronous motor pull-out, lubrication system failure, or other operational difficulties.

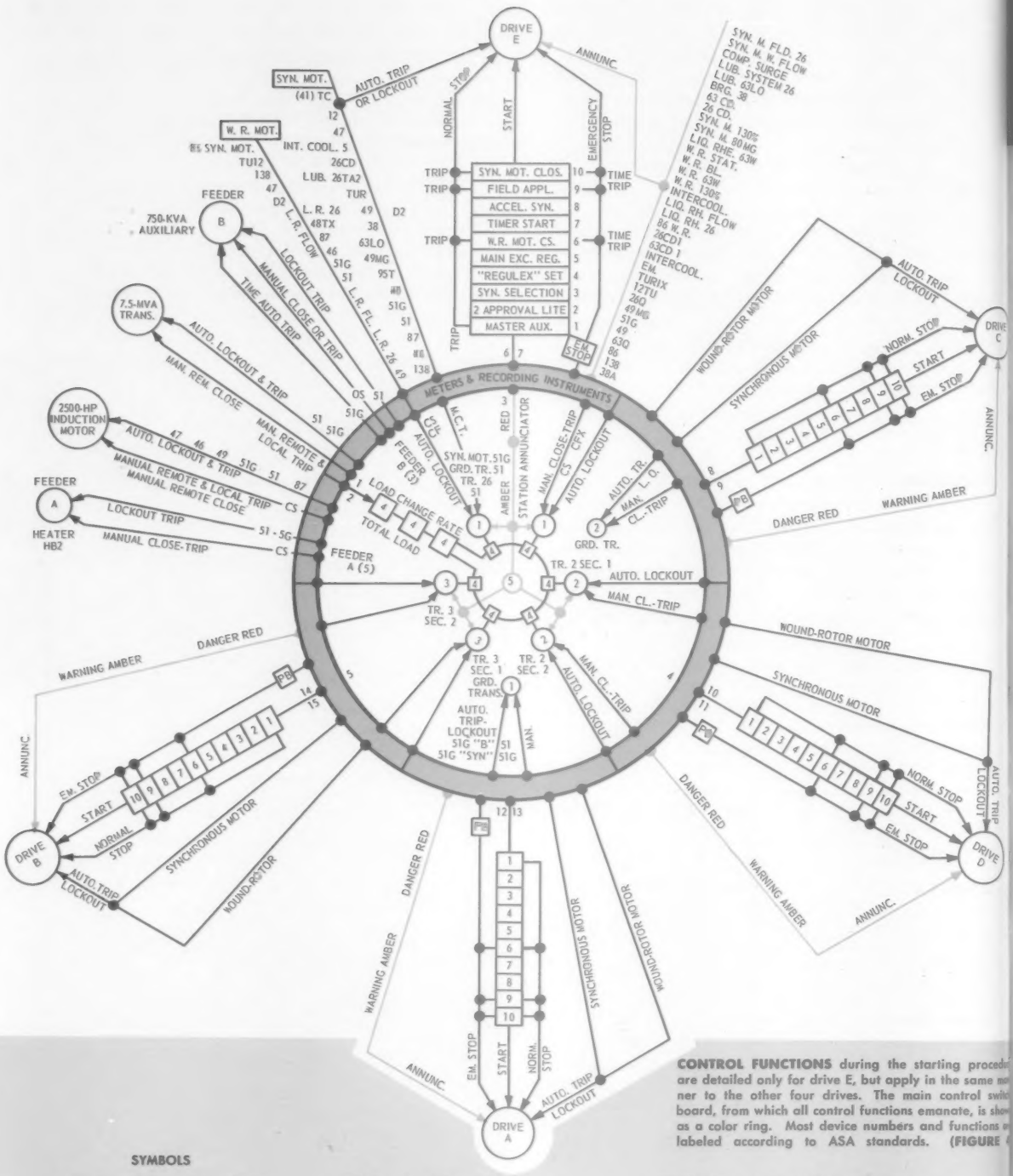
In designing the distribution and control systems for this facility, the maze of details and hidden complexities were simplified through coordination of functions. The value of the installed machinery at GDF — where the highest Mach numbers ever used in a wind tunnel this large will be developed — will be assured by the accuracy and protection its control provides.



POWER is distributed to the five compressor drives through a thirty-cubicle switchgear line-up, only a portion of which is shown. **(FIGURE 2)**



ALL CONTROL FUNCTIONS are centered on this switchboard which is located in a room overlooking the compressor floor. **(FIGURE 3)**



CONTROL FUNCTIONS during the starting procedu are detailed only for drive E, but apply in the same ma ner to the other four drives. The main control switc board, from which all control functions emanate, is show as a color ring. Most device numbers and functions a labeled according to ASA standards. (FIGURE

SYMBOLS

1	Trans. 1 Secondary Circuits
2	Trans. 2 Secondary Circuits
3	Trans. 3 Secondary Circuits
4	Trans. 1, 2, and 3 Secondary Load Totalizing and Change Rate Circuit
30	Station Annunciator
CS	Control Switch
CF	Central Facilities' Contact
LR26	Liquid Rheo. Temperature
LRFL	Liquid Rheo. Flow
T2	Wind-Tunnel Overspeed
TC	Trip Coil Aux. Relay
5	Time-Delay Shutdown Relay
26CD	Compressor Discharge Temperature
26Q	Lub. Oil Temperature
TUR	Reverse Tunnel Rotation
D2	Time-Delay Shutdown Relay
63Q	Lub. Oil Pressure
49MG	Thermal Overl. Relay Syn. Mot. Exc.
95T	Out-of-Step Relay
63CD	Compressor Disch. Pressure
80	Voltage Relay Syn. Mot. Exc.
63W	Water Pressure
EM	Emergency Pushbutton Stop
38	Bearing Temperature Recorder
138	Bearing Temperature Relays
WR	Wound-Rotor Starting Motor

For all other symbols see NEMA Standards.

How To Increase Step Regulator Ratings

by **W. C. SEALEY**
Chief Engineer
Transformer Dept.
and
R. D. OKERBERG
Transformer Dept.
Allis-Chalmers Mfg. Co.

Selecting the right regulating range for power and distribution regulators may provide a means of carrying heavier loads without increasing regulator size.

CAPABILITY of this 750-kva, 13,800-volt, three-phase power voltage regulator is actually greater than its nameplate indicates if less than the full plus or minus 10 percent regulating range is utilized.

FEEDER VOLTAGE REGULATORS, like other transformers, have a rated nameplate current. They also have higher capabilities without sacrifice of life when operated at load factors of less than 100 percent or when the ambient temperature is below 30 C. Such loads are illustrated in Figure 1 and are described more fully in the Proposed American Standard Guide C57.35 (1949).

In addition to these loads, regulators have additional capacity without loss of life when they raise or lower the voltage less than the full range of regulation. Since the losses of a step regulator decrease as the tap changer moves closer to the neutral position, it is possible to increase the current ratings on these taps. The amount of increase allowable without exceeding ASA temperature rises depends upon the design of the regulator.

Single-core, two-winding units

A majority of regulators are built with a single core having an exciting winding and a tapped series winding, as shown in Figure 2. The regulator is so designed that the oil rise will not exceed 50 C and the hottest copper 65 C when operated at rated voltage and current, and maximum regulation. For this condition, let

W_1 = watts copper loss in the exciting winding on the full 10 percent tap position at rated current.

W_2 = watts copper loss in the series winding on the full 10 percent tap position at rated current.

W_3 = watts copper loss in the preventive autotransformer, tap-changing mechanism, and bushing leads at rated current.

F = no-load loss, or excitation loss, in watts.

N = per unit portion of tap range in use.

When operating on reduced tap, the exciting winding current is proportional to the tap position. Consequently, the copper loss in the exciting winding is proportional to N^2. The current in the series winding is the line current, but it flows through only that portion of the series winding in use. The copper loss in the series winding is then proportional to N. The copper loss of the preventive autotransformer, mechanism, bushing leads, and the no-load loss are unaffected by tap position.

The total loss on the 10 percent position equals

$$W_1 + W_2 + W_3 + F$$

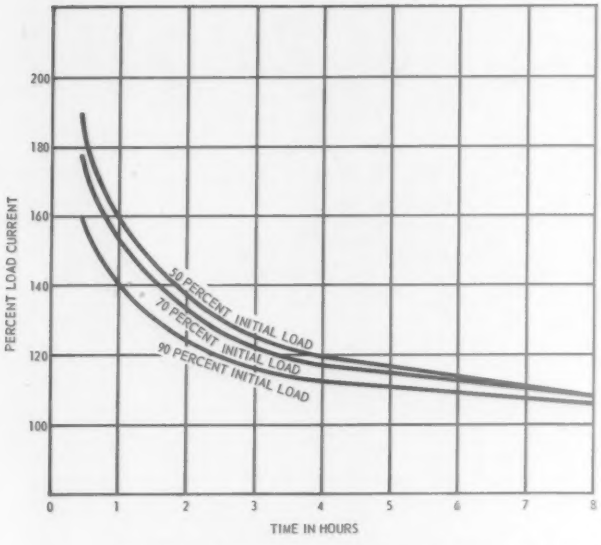
The total loss on any other tap is equal to

$$I^2 (W_1N^2 + W_2N + W_3) + F$$

where I is expressed in per unit of rated current at the 10 percent tap. The oil rise is proportional to the total loss to the 0.8 power, and the gradient between hot-spot copper and oil is proportional to the current to the 1.6 power. To prevent the temperature rises from exceeding those at the full tap position, the following relationship must hold: (1)

$$\left[\frac{I^2(W_1N^2 + W_2N + W_3) + F}{W_1 + W_2 + W_3 + F}\right]^{0.8}(50) + I^{1.6}(15) = 65$$

When the regulator is operating at a reduced tap position, the allowable current depends upon the loss rela-



LOW LOAD FACTORS increase the regulator's capability within its rating without exceeding safe temperature limits. **(FIGURE 1)**

tionship in the regulator. The following values were selected from a large number of designs to give conservative results:

W_1	0.24
W_2	0.36
W_3	0.10
F	0.30
Total	1.00

Using the above values in (1), the allowable current on each tap position is shown as curve *A* in Figure 3. This shows that a considerable increase in current is possible with a reduction in tap position.

Vari-Amp regulators

The change in losses with tap position is utilized in *Vari-Amp* regulators. The size of the series winding is increased proportionally to the current rating, leaving the exciting winding unchanged. The gradient between hot-spot copper and oil is designed for 15 degrees at the maximum current rating. Such regulators are built to carry 160 or 200 percent current at ± 5 percent regulation. Those built for 200 percent current rating inherently have a current capacity greater than 100 percent at the full tap position. The regulator is not given this rating because of the short-circuit limitation. The allowable current for *Vari-Amp* regulators is shown by curves *B* and *C* in Figure 3.

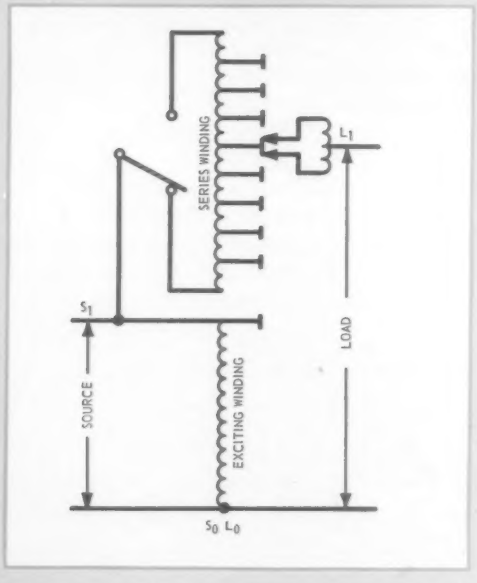
Two-core, three-winding regulators

Regulators with higher current ratings are often built with two cores and three windings, as in Figure 4. The series-parallel connection on the series transformer allows the regulator to be connected either for ± 10 percent regulation and 100 percent current, or for ± 5 percent regulation and 200 percent current. Standard regulators have only one connection for 10 percent regulation. The losses on such regulators also vary with the tap position, although not to the same degree as smaller regulators. For this condition, let

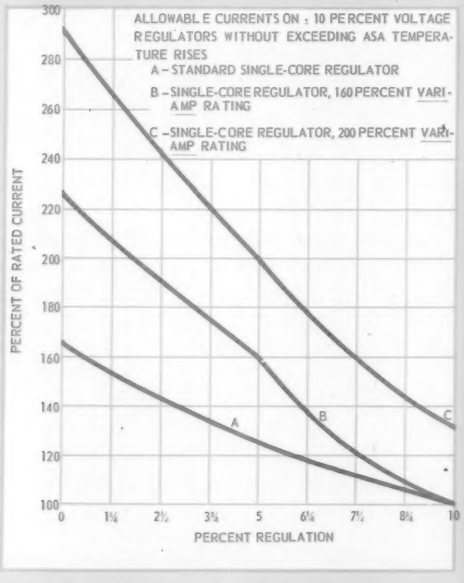
W_1 = watts copper loss in the exciting winding on the full 10 percent tap position.

W_2 = watts copper loss in the series transformer on the full 10 percent tap position.

W_3 = watts copper loss in the preventive autotransformer, tap-changing mechanism, and bushing leads on the full 10 percent tap position.



SINGLE-CORE, two-winding regulators are the most common type installed. One phase of this type regulator is shown. **(FIGURE 2)**



***VARI-AMP* REGULATORS** are built to carry 160 to 200 percent of rated current with plus or minus 5 percent regulation. **(FIGURE 3)**

F_1 = watts core loss in the exciting transformer on the 10 percent tap with rated voltage applied.

F_2 = watts core loss in the series transformer on the 10 percent tap with rated voltage applied.

When operating on reduced tap, the current in the series transformer, tap-changing mechanism, and preventive autotransformer remains the same, and hence the losses are the same. The current distribution in the exciting winding changes, however, and

$$\text{Copper loss in exciting winding} = \frac{N(1.125 - N)}{0.125} W_1 \qquad (2)$$

The voltage on the series transformer varies with tap position, and the core loss varies as the square of the voltage, or

$$\text{Core loss in series transformer} = N^2 F_2 \qquad (3)$$

The core loss in the exciting transformer is independent of load or tap position, so

$$\text{Total loss} = I^2 \left[\frac{N(1.125 - N)}{0.125} W_1 + W_2 + W_3 \right] + F_1 + N^2 F_2 \qquad (4)$$

Loss ratios to give conservative overloads on two-core, three-winding regulators are

W_1	0.04
W_2	0.58
W_3	0.07
F_1	0.14
F_2	0.17
Total	1.00

The allowable loads on such regulators are plotted in Figure 5. These regulators have little increase in load capacity on the reduced range taps because of the relatively high copper losses in the series transformer which do not change with tap position.

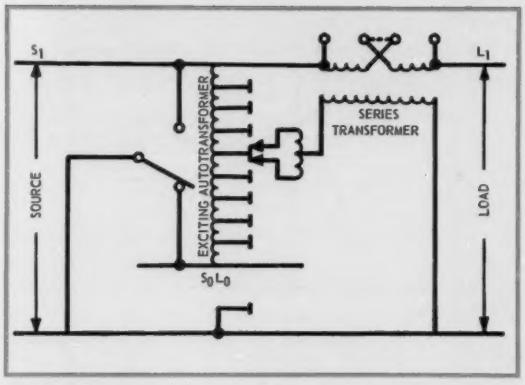
Two-core, four-winding regulators

Regulators rated greater than 15 kv are built with two cores and four windings, as in Figure 6. They are normally built for ± 10 percent regulation, and special units may have a series-parallel terminal board to allow ± 5 percent regulation at 200 percent current. The losses in this type of regulator also vary with tap position. For this condition, let

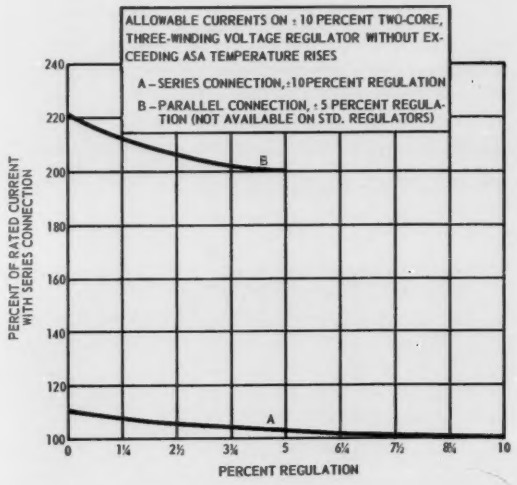
W_1 = watts copper loss in the primary winding of the exciting transformer on the full 10 percent tap position.

W_2 = watts copper loss in the tapped secondary winding of the exciting transformer on the full 10 percent tap position.

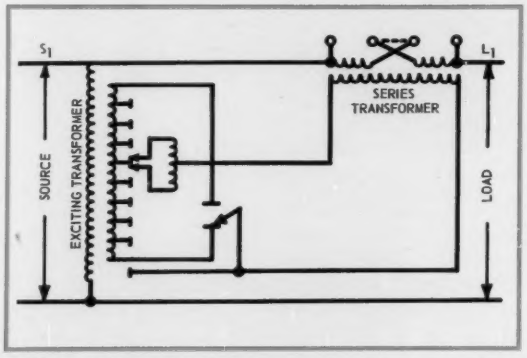
W_3 = watts copper loss in the series transformer on the full 10 percent tap position.



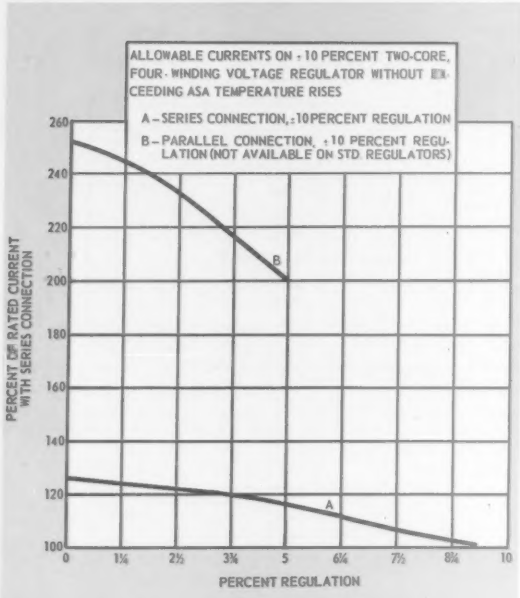
SERIES-PARALLEL arrangement in two-core, three-winding regulators permits connection for either plus or minus 10 percent at 100 percent load, or plus or minus 5 percent at 200 percent load. **(FIGURE 4)**



REGULATOR CAPABILITY changes little with changes in tap position when either the parallel or series connection of two-core, three-winding type regulator shown in Figure 4 is used. **(FIGURE 5)**



HIGHER VOLTAGE REGULATORS are built with two cores and four windings. They normally provide only plus or minus 10 percent regulation, but plus or minus 5 percent units are available. **(FIGURE 6)**



PERMISSIBLE LOADS vary more with the two-core, four-winding type than with two-core, three-winding regulators. **(FIG. 7)**

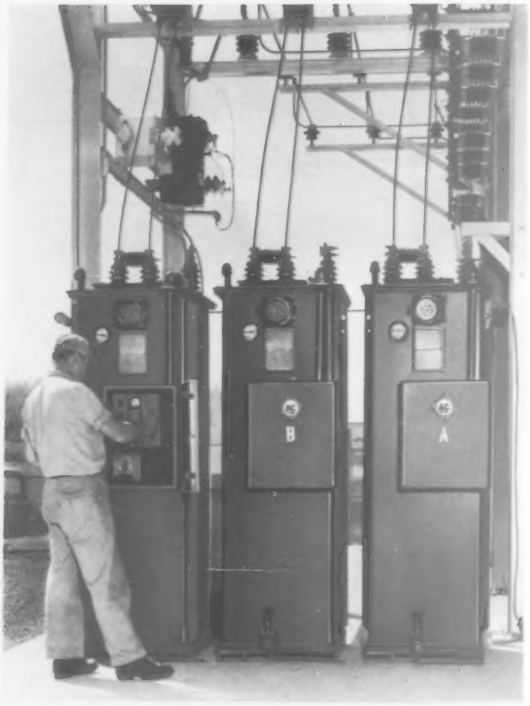
W_4 = watts copper loss in the preventive autotransformer, tap-changing mechanism, and bushing leads.

F_1 = watts core loss in the exciting transformer on the 10 percent tap position with rated voltage.

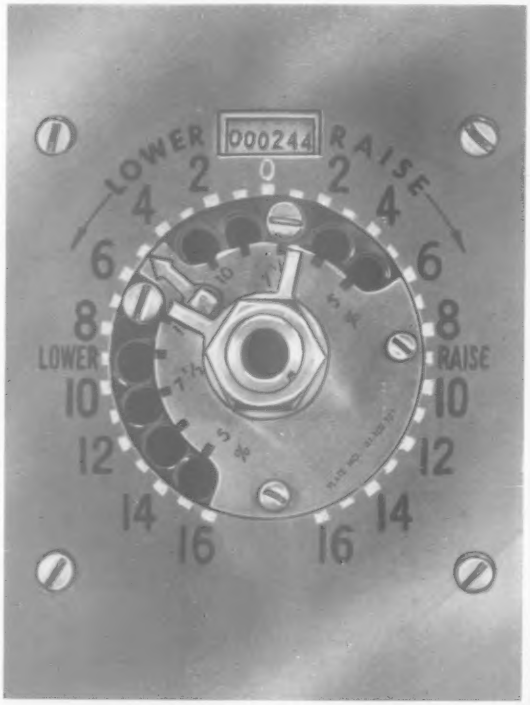
F_2 = watts core loss in the series transformer on the 10 percent tap position with rated voltage.

When operating on reduced tap, the current in the series transformer, tap-changing mechanism, and preventive autotransformer remains the same. Thus, these losses are unaffected by tap position. The current in the primary winding of the exciting transformer is proportional to the tap position, so the losses are proportional to N^2. The current in the tapped secondary winding of the exciting transformer flows through only that portion of the winding in use. The copper loss in this winding is then proportional to N. The voltage on the series transformer is proportional to N, and so the no-load loss of the series transformer is proportional to N^2. The no-load loss of the exciting transformer is independent of tap position, so

$$\text{Total loss} = I^2(W_1N^2 + W_2N + W_3 + W_4) + F_1 + F_2N^2 \qquad (5)$$



VOLTAGE of 2000-kva, 12-kv rural substation is regulated by three single-phase units. Regulators have conveniently located tap position indicators with *Vari-Amp* controls. **(FIGURE 8)**



UPPER AND LOWER LIMITS of regulating range can be adjusted independently. Limit switch trip pins can be placed in the 10, 8¾, 7½, 6¼, or 5 position on both raise and lower sides. **(FIGURE 9)**

Loss ratios to allow conservative overloads for two-core, four-winding regulators are

W_1	0.16
W_2	0.12
W_3	0.36
W_4	0.04
F_1	0.20
F_2	0.12
Total	1.00

Using the above loss ratios, the permissible loads with reduced regulation are as shown in Figure 7.

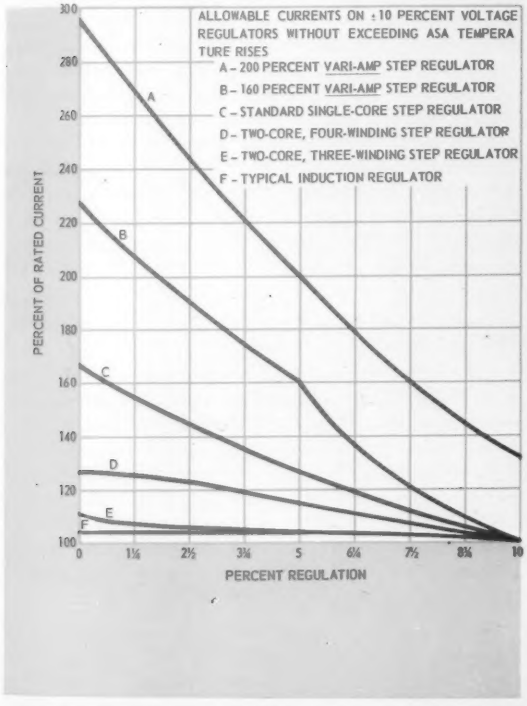
Capabilities applied

Application of the foregoing can result in economy to the users of voltage regulators. Proper selection of substation transformer ratios allows the regulator to operate nearer the neutral position with inherently greater load capacity. The limit switches on regulators with the *Vari-Amp* feature can be adjusted to limit the amount of regulation to 10, 8¾, 7½, 6¼, or 5 percent. These limits may be set differently for the raise and lower direction, and are easily accomplished by adjusting the limit switch trip pins behind the position indicator window. The indicator is shown in Figures 8 and 9. When further reduction in regulation is desired, the position indicator may be modified to include extra positions.

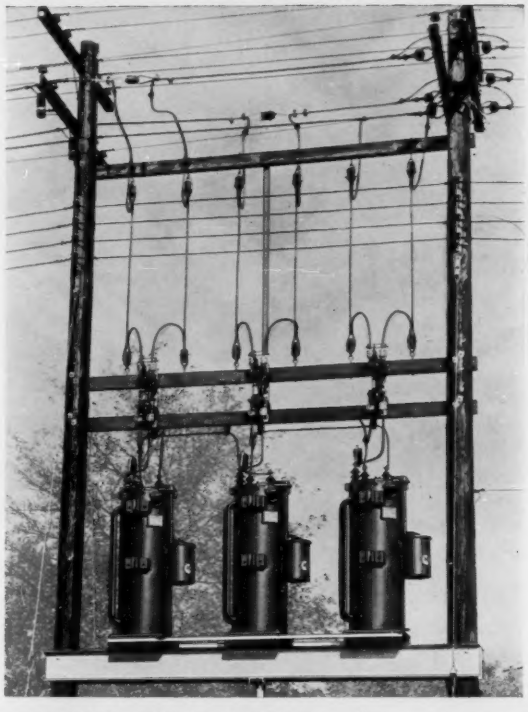
Regulators without the *Vari-Amp* feature also have increased capacity with reduced regulation, as previously illustrated. This increased capacity can be utilized by installing the regulator where it will not use its full tap range under normal conditions. If full range of regulation is needed under emergency or unusual conditions, the full regulator range is available. If this occurs during peak load conditions, the regulator may suffer some loss of insulation life. However, since the regulator often operates at or near the neutral position during light load periods, the complete load cycle is not as severe for a regulator as for a similarly loaded transformer. In any case, proper voltage is usually more desirable than providing poor voltage at peak load by limiting the regulator range. When regulator life is more important than proper voltage, the limit switches on standard regulators can be modified to limit regulation as desired.

The application of such loads will result in increased arcing duty on the tap-changing mechanism. When these loads are carried for prolonged periods of time, increased maintenance and greater contact wear may result. In most cases, this cost will be more than compensated for by the increased load capacity.

The constants used to prepare Figures 3, 5, and 7 were selected from a wide variety of designs to give conservative overloads applicable to Allis-Chalmers regulators. For convenience, Figure 10 has been prepared to show the overload capacities of all available voltage regulators. A curve for a typical induction regulator has been included. Application of these curves can result in increased economy to the users of voltage regulators.



LIMIT SWITCH TRIP PIN LOCATION for each application of step regulators should be made with regulator capability in mind. These curves show allowable currents for various taps. **(FIGURE 10)**



DISTRIBUTION VOLTAGE REGULATOR capability can also be extended by limiting the regulating range. These 50-kva, 2500-volt, 200-amp units serve a Midwest distribution system. **(FIGURE 11)**

PART II

MOTOR STARTING...

Methods For Reducing Initial Kva

LINE-UP of full-voltage, 440-volt synchronous motor controllers having 50,000-amp interrupting capacity drawout circuit breakers and common ac power bus.

by **H. W. CORY**
Chief Engineer
Control Department
and
T. F. BELLINGER
Control Department
Allis-Chalmers Mfg. Co.

Various starting methods are compared to aid in selection of motor controllers.

SELECTING A MOTOR CONTROLLER for a specific application involves a study of the motor, load and power distribution system. The general types of standard motor controllers are full voltage, autotransformer, resistor, reactor, part winding, wye-delta, and wound rotor.

Full-voltage starters are always first choice where the power distribution system, the load and the motor design will tolerate the initial inrush current or sudden application of load inherent in full-voltage starting.

Autotransformer starting is common choice

Where a reduction of the starting kva is required, autotransformer-type controllers are the most common choice.

A typical circuit for a low voltage autotransformer squirrel-cage controller is shown in Figure 1. These controllers are available in ratings up to several hundred horsepower for both the low and high voltage classes. The autotransformers have intermittent ratings for light, medium, or heavy-duty applications and have voltage taps in these duty classes as shown in Table I. Either two or three-leg starting autotransformers are used in three-phase controllers. The diagram of a two-leg type, commonly used in standard motor controllers, is shown in Figure 1. This type circuit causes about 15 percent voltage unbalance while the unit is supplying reduced voltage to the motor terminals. Except in very special applications, this unbalance is not a problem. Since the two-leg units are less expensive, they are most widely used.

The current taken from the line to start polyphase motors is reduced by reducing the voltage to the motor terminals while the motor accelerates to a definite speed or current point. Voltage reduction is accomplished in these motor controllers by connecting the motor to the line through an autotransformer, as shown in the diagram. The voltage on the motor terminals during starting is set by the tap connections made to the autotransformer. Most controllers are equipped with medium-duty units and are connected at the factory to the 65 percent taps. The controller will automatically disconnect the autotransformer from the circuit and connect the motor directly to the line. Definite time relays or current relays control the transfer.

When starting a motor with an autotransformer-type controller, the minimum voltage tap that will adequately accelerate the motor and its connected load is used. The motor should reach its maximum speed before it is transferred to full voltage. Correct transfer timing minimizes the line disturbance and reduces arcing on the controller

line switches. When the controller transfers to full voltage, the circuit to the motor is completely interrupted and reconnected. If the motor has not accelerated sufficiently, the current at transfer to full voltage can be much greater than the current taken from the line at the instant of starting and can be nearly as much as full-voltage locked-rotor current. This condition can be seen in the full-voltage starting current curve and the 50 percent autotransformer-current curve in Figure 1, Part I. Transfer to full voltage was purposely shown at 1100 rpm to illustrate how the current can be higher than at the instant of starting. At zero speed the line current is only 380 amperes, but at 1100 rpm the line current jumps to 550 amperes. If transfer would occur at 1000 rpm, the line current would be 820 amperes. The autotransformer voltage tap and the transfer point are selected to obtain a current at transfer that does not exceed the zero speed current. If the current is exceeded, the advantages of reduced-current starting are lost. The proper autotransformer tap and transfer setting are usually selected by trial.

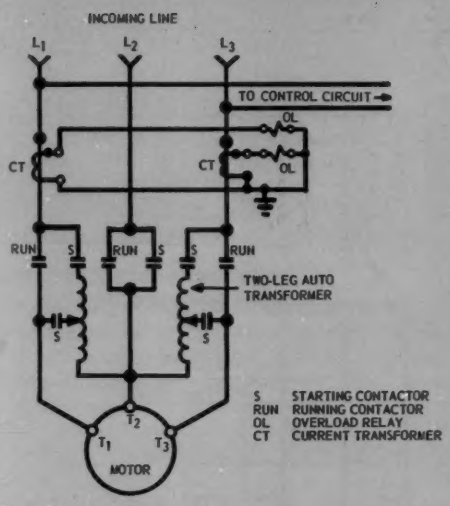
Method provides more torque

The autotransformer method of starting provides greater starting torque per ampere than any other type of reduced-current starting. The current taken from the line is proportional to the (percent starting voltage)^2/100. When the 50 percent tap is used, only 25 percent of the full-voltage starting current is taken from the line, while the 80 percent tap will allow 64 percent of the full-voltage starting current. This relation is shown in Figure 2. Assume that the full-voltage locked-rotor starting current of a motor is equal to I. If a 50 percent autotransformer tap is to be used for starting, 50 percent of the line voltage $E/2$ will appear on the motor terminals. If the voltage is reduced by one-half, the current through the motor winding will be just half the value it would have been on full voltage, or $I/2$. The volt-amp output of the autotransformer is then $E/2 \times I/2$. Assuming there is no loss in the autotransformer, the primary input must equal the output. Since the primary voltage is E, or full voltage, $EI/4 = E \times I$ (primary). I (primary) $= I/4$, or 25 percent of the full-voltage locked-rotor current. The magnetizing current of autotransformers is about 5 to 10 percent of total line current and must be added to the value of the line current if accurate calculations are required.

The autotransformer starting is called "open transition starting" because of the open circuit condition during transfer to full voltage. The open circuit condition has some advantage due to possible current increments during transfer, particularly at low speeds. A three-leg autotransformer circuit is available to provide closed transition starting. However, starters with this circuit are special and considerably more expensive.

Primary reactor and resistor starting compared

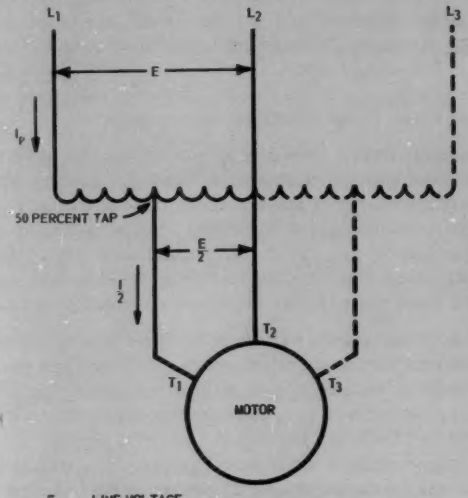
Another method used to reduce starting current consists of placing a reactor or resistor element in series with each phase of the motor to reduce the voltage on the motor terminals. The elements remain connected until the motor has accelerated sufficiently so that transfer to full voltage can occur with minimum line disturbance. Transfer can



MORE STARTING TORQUE per ampere drawn from the line is provided by autotransformer controllers than the other reduced-voltage types of control. **(FIGURE 1)**

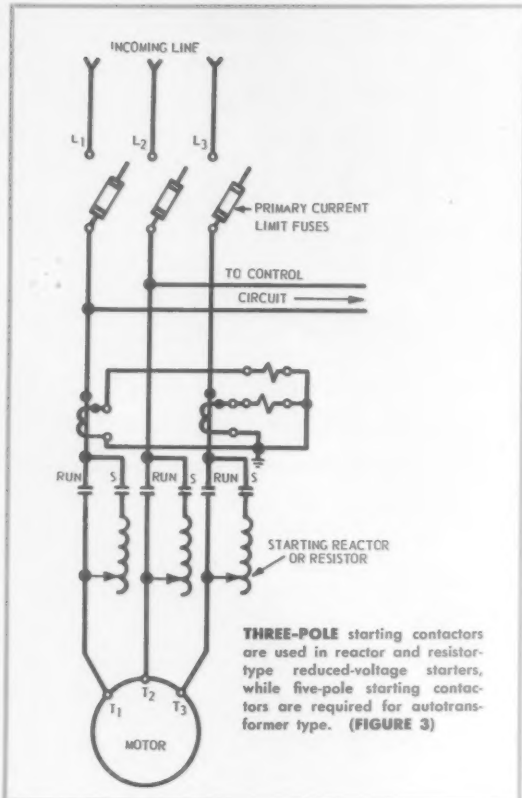
TABLE I
AUTOTRANSFORMER AND REACTOR DESIGN CLASSIFICATION

Service Classification	HP Rating of Motors	Starting Taps (25 and 60 Cycles) Approximate Percent of Line Voltage
Heavy Duty	All Ratings	Taps Shall Be Determined By Application
Medium Duty	50 Horsepower and Less	65-80
	Above 50 Horsepower	50-65-80
Light Duty	All Ratings	30-37.5-45

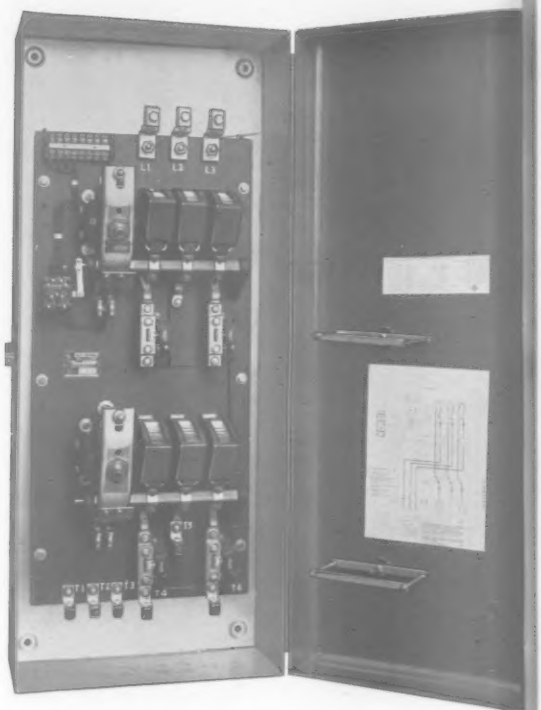


E = LINE VOLTAGE.
I = LOCKED-ROTOR STARTING CURRENT.
I_p = AUTOTRANSFORMER PRIMARY CURRENT.
$\frac{E}{2} \times \frac{I}{2}$ = AUTOTRANSFORMER OUTPUT.
$E \times I_p$ = AUTOTRANSFORMER INPUT.
$\frac{E}{2} \times \frac{I}{2} = E \times I_p$ (ASSUMING NO MAGNETIZING CURRENT).
$I_p = \frac{1}{4}$ OR 25 PERCENT FULL VOLTAGE LOCKED-ROTOR CURRENT.

STARTING LINE CURRENT is percent of voltage tap squared times locked-rotor current divided by 100. Autotransformer magnetizing current is neglected. **(FIG. 2)**



THREE-POLE starting contactors are used in reactor and resistor-type reduced-voltage starters, while five-pole starting contactors are required for autotransformer type. **(FIGURE 3)**



PART-WINDING MOTORS require increment-type starters. While starting autotransformers, reactors and resistors are eliminated, no starting current adjustment is available. **(FIGURE 4)**

be accomplished either with time-delay relays or with current relays similar to the autotransformer-type controllers. After transfer has been completed, the starting elements are either disconnected from the circuit or shorted out during normal operation. The transfer from reduced voltage to full voltage occurs without any interruption in the power connection to the motor. These controllers are referred to as "closed transition starting units."

Starting reactors have intermittent ratings according to duty requirements, as shown in Table I. Resistor-type starters are somewhat less expensive than the reactor type but are available only in low voltage ratings in sizes up to motors having full-load currents under 600 amps. For higher voltages or currents, insulation, space factors, and power losses make the use of primary resistors impractical.

Reactor and resistor starting do not limit starting current to the same extent as autotransformer starting. The starting currents with reactor or resistor are directly proportional to the voltage taps. A 50 percent reactor or resistor voltage tap limits the starting current to 50 percent of the full-voltage value, whereas the 50 percent autotransformer tap limits the current to only 25 percent of the full-voltage value. However, the closed transition feature can be of some importance on systems sensitive to small voltage dips. Even though the current at transfer may be greater than starting current, the rise in current is only an addition to the starting current, and not from zero as it was for the autotransformer starting. This condition is shown for the reactor starting curve in Figure 1, Part I. The current jumps to 500 amps at transfer, but this is only a step of 230 amps above the starting current. Even if transfer had occurred at 100 rpm, the full-voltage current would only be a step of 720 amps above the starting current. Both reactor and resistor methods permit balanced currents for motor starting.

Most standard reactor and resistor starters are designed for two-step starting — one step on reduced voltage and the final step to full voltage. Figure 3 shows a high voltage primary reactor starter. Both reactor and resistor controllers are readily available with more than two starting steps. The current change per step decreases proportionally with the number of steps used.

A primary resistor starter is less expensive than a comparable reactor starter when both are available in the same ratings. The reactor type is more efficient and will produce slightly more starting torque.

A comparison of the three most common types of reduced-voltage starters is shown in Table II.

Part-winding starting evaluated

The stator windings of most integral-horsepower ac motors are made with two or more conductors in parallel per

phase. The conductors are normally tied together inside the machine and only single-phase terminal leads are brought out for each phase. It is possible to bring each individual phase conductor out to terminals and make the parallel connection for each phase external to the motor. If a single conductor of each phase were connected to line voltage, only a portion of normal starting current would flow. If there were two conductors per phase, each would carry half of the motor current. If one set of conductors were connected, the starting current would be just half that of a standard motor. The current for each set of conductors per phase is inversely proportional to the number of conductors per phase.

Part-winding motors are usually started by connecting each set of phase conductors to the line in sequence until all conductors for each phase are in parallel, after which the motor will be ready for normal operation. The sequence is usually controlled by timing relays set for short time intervals of 1 to 5 seconds. The purpose of part-winding starting is not so much to provide reduced current for acceleration of the motor, but primarily to provide smaller increments of starting current. The phase conductors are not capable of carrying current individually for more than a few seconds. Often on three-step starting the first step interval is set for a second or less. The motors usually do not break away under these conditions, but the purpose of reducing the magnitude of the starting current into a series of small increments has been achieved.

Part-winding starting is not widely used. There are some sizes of low voltage motors and controllers available, but high voltage units are seldom used except in some phases of the cement industry. Controllers for use with part-winding motors such as shown in Figure 4 are usually lower priced than similar controllers of the autotransformer, reactor, or resistor types because current-limiting elements are not required. However, motors for part-winding starting are generally more expensive.

Wye-delta starting used abroad

In a method frequently used in Europe and South America ac motors are started by connecting the motors to the line with the stator windings connected in wye. After the motors have accelerated to their maximum speed, the windings are reconnected in delta for normal operation. This permits the locked-rotor current to be reduced by a factor of $1/\sqrt{3}$, or 57.5 percent of normal locked-rotor current. This type of starting is open transition and does not offer much advantage, since only 57.5 percent starting point is possible. Both ends of each motor phase winding, or a total of six terminals, must be brought out. This arrangement is costly and is not standard in this country. Wye-delta starting is not recommended for general application.

Wound-rotor motors provide smooth start

All of the starting methods previously covered were for the starting of either squirrel-cage induction motors or synchronous motors. Wound-rotor induction motors are used to obtain smooth starting and acceleration to protect the driven equipment or power systems and to obtain speed control.

Although wound-rotor motors are started directly across the line, the motor controllers can cause them to accelerate smoothly and efficiently, with initial starting currents less

TABLE II

GENERAL COMPARISON OF STARTING CONDITIONS BETWEEN THREE TYPES OF REDUCED-VOLTAGE STARTERS

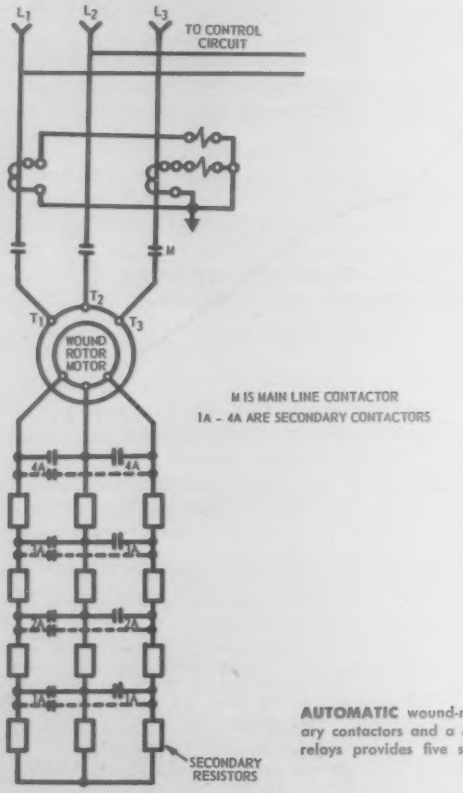
Characteristic	Autotransformer Type	Primary Resistor Type	Reactor Type
Starting line current at same motor terminal voltage	Least	More than autotransformer type	
Starting power factor	Low	High	Low
Quantity of power drawn from the line during starting	Less	More than autotransformer type	
Torque	Torque increases slightly with speed	Torque increases greatly with speed	
Torque efficiency	The autotransformer-type starter provides the highest motor starting torque of any reduced-voltage starter for each ampere drawn from the line during the starting period.	Low	Low
Smoothness of acceleration	Motor is momentarily disconnected from the line during transfer from start to run.	Smoother. As the motor gains speed the current decreases. Voltage drop across resistor or reactor decreases and motor terminal voltage increases. Transfer is made with little change in motor terminal voltage.	
Cost	Equal	Lower in small sizes, otherwise equal	Equal
Ease of control	Equal	Equal	Equal
Maintenance	Equal	Equal	Equal
Safety	Equal	Equal	Equal
Reliability	Equal	Equal	Equal
Line disturbance	Varies with line conditions and type of load		

than that required for other types of motors. The rotor or secondary slip rings are connected to banks of definite values of resistance for each of the secondary phases. A diagram of a typical automatic controller for a wound-rotor motor is shown in Figure 5. These motors are started with the total resistance in the circuit. By shorting out specific sections of the secondary resistance in sequence, the motors accelerate through a series of definite speed-torque characteristic points corresponding to the number of resistance steps and the value of the resistance at each step. The number of steps, or speed points, is always one greater than the number of shorting switches. The secondary characteristics and control components can be identical for similar motors of equal horsepower rating even though the stator voltage ratings may be widely different.

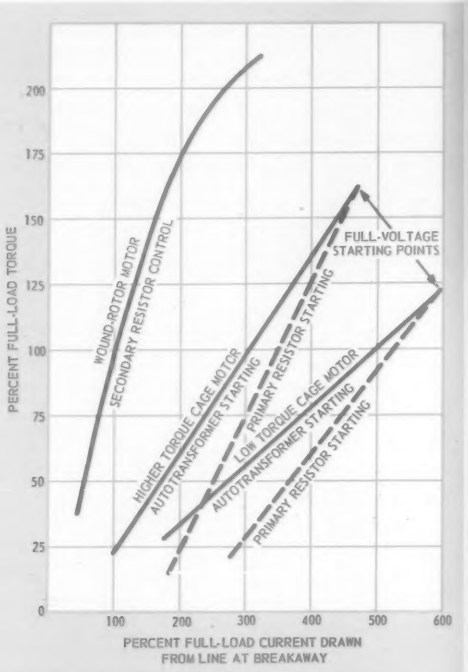
The number of resistance steps can be increased or decreased depending upon the application. If the smoothness of starting is to be improved, a greater number of steps are used. In a recent application three 300-hp wound-rotor motors were used to drive a single mile-long conveyor belt in a mine. The motors were accelerated to full speed in 36 steps to prevent overstressing the belt. Stepless starting can be obtained by the use of liquid rheostats in place of secondary resistors and the shorting switches. This type of controller is comparatively expensive and is used only for special applications.

Starting current of wound-rotor motors can be limited to specific values by the design of the secondary resistor banks. The duty cycle of the application determines the thermal capacity that must be built into the resistors. Lower inrush currents or a more severe duty cycle increases both size and cost of the secondary resistor banks. If speed regulation of the wound-rotor motor is required, the resistors must be designed for continuous duty for the step where speed control is desired. Regulating duty resistors are designed for a fully loaded motor. If the motor does not draw full-load power, the specified degree of speed regulation cannot be obtained without additional resistance.

Wound-rotor motors and their controllers are more expensive than cage units, but their use should be considered when severe starting problems are anticipated. A comparison of their torque characteristics to those of comparable cage motor starters is shown in Figure 6. The wound-rotor motors and control permit flexible speed adjustment and reduce starting-current increments.



AUTOMATIC wound-rotor controller having four secondary contactors and a corresponding number of time-delay relays provides five steps of acceleration. **(FIGURE 5)**



WOUND-ROTOR MOTORS supply considerably more starting torque per ampere drawn from the line than do cage-type induction motors of the same rating. **(FIGURE 6)**

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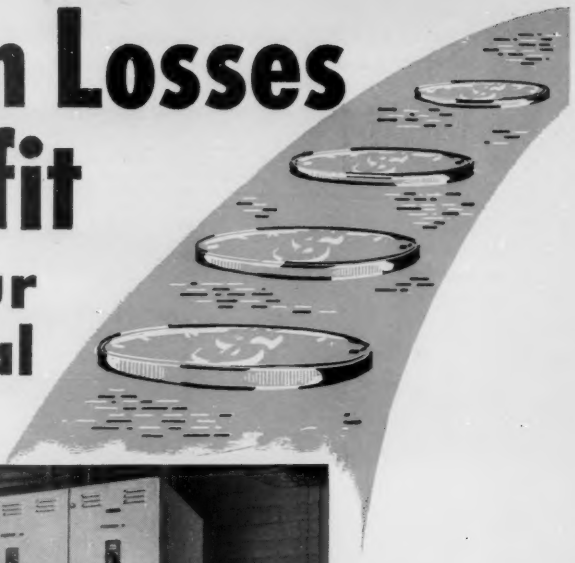

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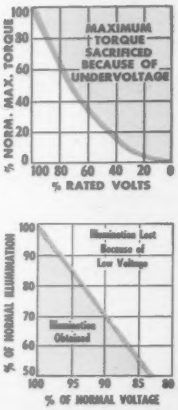

Charts Show Losses when voltage is low. Upper, torque loss at machines. Lower, illumination lost. Placing unit substations at load centers shortens low voltage cable, improves voltage, and makes future changes simpler, less costly than with many outmoded plant arrangements.

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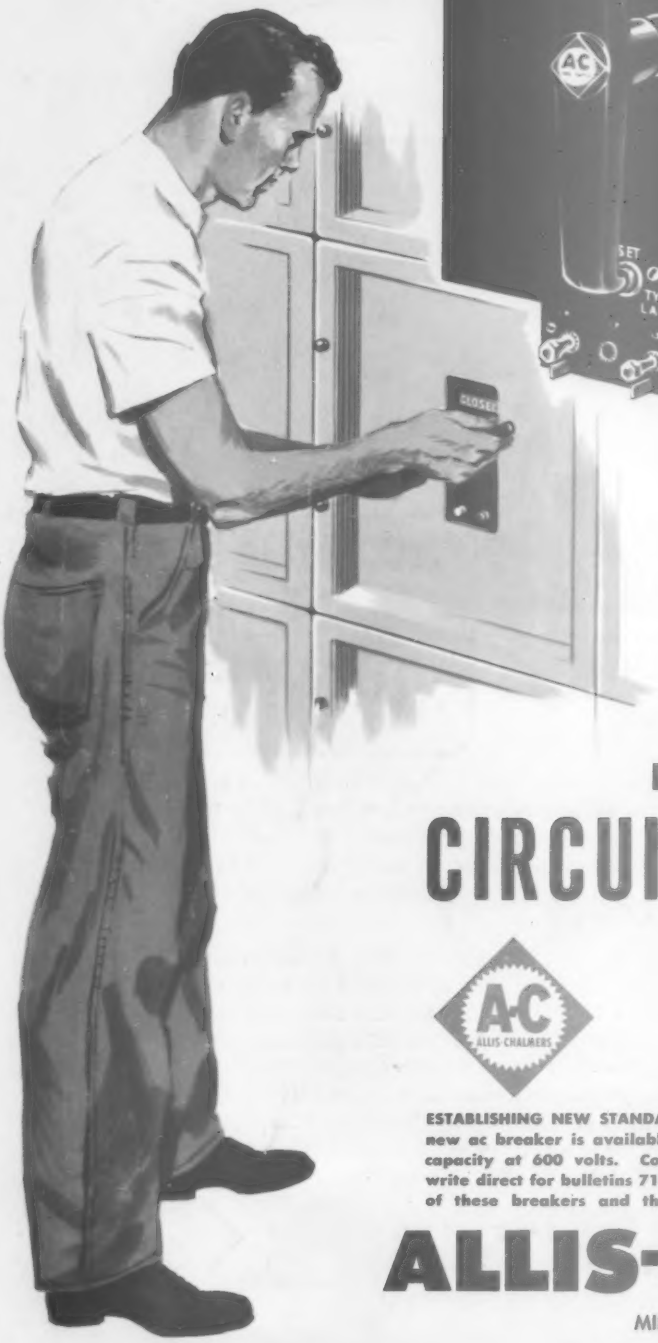

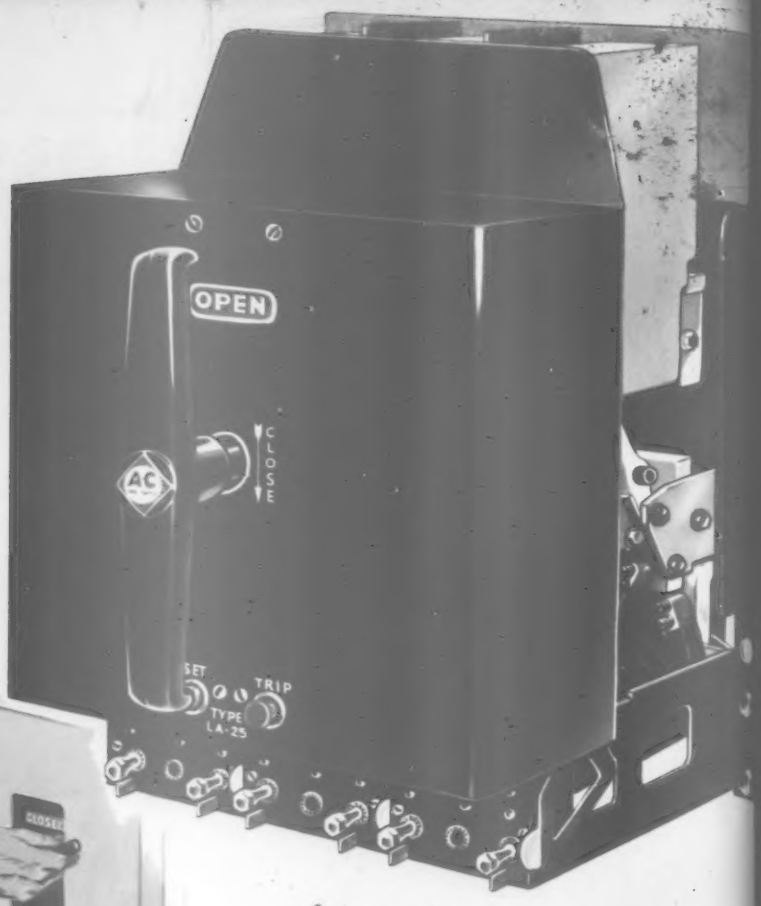

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